American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

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To cite this article: RIEDAR K. OESTENSTAD , H. KENNETH DILLION & LAURA L. PERKINS (1990) Distribution of Faceseal Leak Sites on a Half-Mask Respirator and Their Association with Facial Dimensions, American Industrial Hygiene Association Journal, 51:5, 285-290, DOI: 10.1080/15298669091369664

To link to this article: https://doi.org/10.1080/15298669091369664

Distribution of Faceseal Leak Sites on a Half-Mask Respirator and Their Association with Facial Dimensions*

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Faceseal leaks on one brand of half-mask respirator worn by 73 human subjects were identified by deposition of a fluorescent tracer aerosol during a standard quantitative fit test. The identified leaks were categorized according to their location and shape. It was found that about 89% of all observed leaks occurred at the nose or chin or were multiple leaks which included these sites. Fit factors for these types of leaks were significantly lower than for other types of leaks. About 73% of all leaks approximated the shape of a slit rather than a round orifice, and the prevalence of these leaks was affected by gender. Significant association of facial dimensions and leak sites were found. Most of these were attributed to differences in gender, and only a very small percentage were for the facial dimensions used to define the Los Alamos respirator test panel. Significant correlation of facial dimensions and fit factor were found for only three facial dimensions; none of which are used to define the test panel. Evidence of airflow streamlining within the facepiece was observed on 22% of the subjects. Results of this study indicate that respirator leakage is strongly affected by nose and chin leaks, that gender is a factor in how a respirator fits, and that consideration should be given to including nasal dimensions when defining a respirator test panel and selecting a respirator for an individual wearer.

While there has been extensive work conducted to quantify respirator leakage, very little has been reported on the size and shape of respirator faceseal leaks. Yet recent developments in respirator research have been based, in part, on assumptions about these parameters. Also, a significant association of respirator leakage with facial dimensions used to define respirator test panels has not been supported in previous studies. This would indicate that other facial dimensions may be critical in defining a good respirator faceseal. A better understanding of this relationship is critical since the National Institute for Occupational Safety and Health (NIOSH) has proposed to include the use of facial dimensions in test specifications for certifying respirators.[1] A method developed to identify respirator leak sites has been used to study these parameters for human subjects wearing one brand of half-mask, air-purifying respirator.[2]

Recently, several models to predict respirator leakage have been developed.[3-6] In these models, protection factors are predicted by the ratio of total airflow into the respirator facepiece to airflow through faceseal leaks. In general, airflow through the leaks is determined by the equation $Q = K \times P^a$, where Q = flow rate and P = resistance. The flow coefficient (K) represents the dimensions of the leak and various unit conversion factors. The exponent (a) characterizes the type of flow and ranges from 1.0 for laminar flow to 0.5 for turbulent flow.

The values of both the flow coefficient and the exponent for a given leak are determined by its size and shape. These parameters for faceseal leaks on humans are not known but have been approximated by capillaries in prominent mannequin studies of respirator leakage.[7,8]

In the landmark paper on sampling bias in the determination of protection factors, capillaries were used as artificial leaks.[7] Location of leaks was selected only on the basis of experience, and was one of the factors found to have a significant association with sampling bias.

Round tubes and wires placed in the faceseal were used to represent leaks in a study to determine flow characteristics in respirator leaks.[8] It was observed that pressure drop versus flow rate through these types of leaks was nonlinear, indicating that flow was changing from laminar to turbulent. Therefore, the value of the flow exponent was changing. These changes were attributed to leak path geometry. It was also noted that flow rate was proportional to the 2.7 power of leak diameter for the leaks tested.

A method to estimate respirator fit by pressure decay is also based on predicted airflow through round leaks.[9] In this method, airflow into the facepiece is determined from flow equations using the same coefficients and exponents for round capillary leaks. The researchers acknowledge that flow is dependent, in part, on leak shape and additional work is needed to show the extent of this dependence.

Anthropometric dimensions are an important consideration in the design of respirator facepieces.[10] The effect of respirator

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design and facial dimensions on respirator leakage was recognized by researchers at Los Alamos.[11] From extensive quantitative fit test data, they concluded that one type or size of facepiece could not be expected to provide an adequate fit for an entire working population. As a result, anthropometric test panels defined by face length and lip width were established for conducting quantitative fit testing on half-mask respirators.[12] Data from subsequent fit tests utilizing these panels were used to establish assigned protection factors.[13]

However, the relationship of these facial dimensions and respirator fit has never been validated by association with respirator leakage. A study to determine the association of these dimensions with fit factors found a significant correlation coefficient of 0.22 for lip width ($p = 0.30$) but none for face length.[14] However, the correlation coefficient was relatively low, and the findings probably were limited by the assumption that differences in faceseals did not contribute significantly toward variance in protection factors.

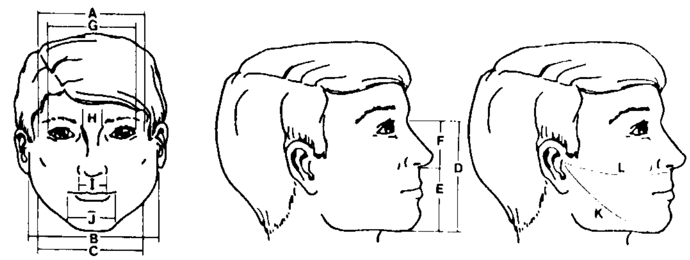
The association of lip width with respirator leakage was also tested as part of a study of workplace protection factors in a copper smelter.[15] No significant association was found between this dimension and the average protection factor for each worker. However, this result was limited in that it was based on a small sample size ($n = 9$).

EXPERIMENTAL MATERIALS AND METHODS

The purpose of this study was to determine the distribution of faceseal leak sites and shapes on a group of 73 subjects wearing one brand of half-mask respirator and to test the association of the identified leaks with the subjects' facial dimensions. One test was performed on each subject according to a protocol developed to identify leaks by the deposition of a fluorescent tracer aerosol at the leak site.[2] The test protocol included (1) measuring facial dimensions, (2) taking preexposure photographs, (3) fitting with a respirator and performing a pressure check, (4) performing a quantitative fit test according to an ANSI recommended method,[16] and (5) taking postexposure photographs and classifying observed leak sites.

The respirator used in the study was the U.S. Safety Series 200 Half-Mask which was available in small, medium, and large sizes (United States Safety Service Co., Kansas City, Mo.). The facepiece size was selected for each subject according to their face length. The respirators were carefully fitted to assure the best possible faceseal. Subjects who had facial features which would result in obvious leak sites or who could not attain a fit factor greater than 10 were not included in the study.

The facial dimensions illustrated in Figure 1 were measured with sliding and spreading calipers and a steel measuring tape. Identification of facial landmarks and measurements were made by one investigator according to training provided by the staff of Anthropometry Research Projects, Inc., of Yellow Springs, Ohio. Before any measurements were made in the study, three sets of measurements of the 12 selected dimensions were performed on a panel of 10 subjects for the purpose of developing experience in locating facial landmarks, making measurements, and determining the reliability of the investigator's measurement techniques.



A. Biectoorbitale Breadth
B. Bizygomatic Breadth (Face Width)
C. Bigonial Breadth
D. Menton-Nasion Length (Face Length)
E. Menton-Subnasale Length (Lower Face Length)
F. Subnasale-Nasion Length (Nose length)
G. Biocular Breadth
H. Nasal Root Breadth
I. Nose Width
J. Lip Width
K. Bitragion-Menton Arc
L. Bitragion-Subnasale Arc

Figure 1—Facial dimensions

Data for each dimension were analyzed by a two-way analysis of variance (two-way ANOVA).[17] As expected, the between-subject variation was significant for all dimensions. There was also significant between-test variation for three dimensions. However, a graph of the residuals for these dimensions indicated that measurements on one subject accounted for most of the variation in these dimensions. These results were considered adequate relative to expected interobservation variability identified in anthropological studies.[18,19]

Measurement consistency was also evaluated during the study by measurements of the 12 dimensions performed on a control subject at selected intervals. These observations were plotted on Shewhart Quality Control graphs, and no trends or values outside the two standard deviation control limits were noted.[17]

Identified leaks were classified according to their location and shape. Leak site categories were around the nose, on the cheeks, under the chin, or a combination of more than one of those sites. There were eight possible categories of single or multiple leak sites. Leak shapes were either point or diffuse: point leaks were whose on which the aerosol was deposited on a small cross sectional area (less than 1 cm) of the face, and diffuse leaks were those where the aerosol was deposited over a large area (greater than 1 cm).

Data recorded on each subject were entered into a spreadsheet, and appropriate parametric and nonparametric statistical analysis performed using True Epistat Statistical Software.[17] Two-tailed tests of hypothesis were performed using an alpha value of 0.05.

Designation of leak sites was considered as a multinomial random variable. The sample distribution was compared to the multinomial distribution using the chi-square goodness-of-fit test with the null hypothesis that each of the eight leak site categories was equally likely to occur ($p_i = 0.125$ for $i = 1, 2, \cdots 8$).[20] Given that a leak occurred, leak shape was a dichotomous variable whose distribution was assumed to be binomial.

RESULTS

Subjects ($N = 73$) included university students, staff, and faculty who volunteered to participate in the study. Their average age

TABLE I
Gender and Race Distribution of Test Subjects

Race	Male	Female	Total
Asian	7	2	9
Black	3	6	9
White	25	25	50
Other[A]	4	1	5
Total	39	34	73

[A]The race category of "Other" included Hispanics and Asian Indians.

was 30.6 years, and ranged from 21 to 50; 10 of the subjects had experience in wearing respirators in workplace settings. The gender and race distribution of the sample is shown in Table I.

Figure 2 is a plot of the dispersion of test subjects according to their face length and lip width relative to the Los Alamos respirator test panel.[12] Although it follows the same general pattern, facial dimension distribution of the sample is skewed to the upper half of the test panel. This difference could be attributed to true differences between the populations used to establish the panel and the sample population or to systematic differences in measurement technique by the investigator.

Table II summarizes observed respirator leak sites for all subjects and gender subsets. Statistical analysis of race subsets was not considered appropriate because of the small number of subjects in these groups. A chi-square goodness-of-fit test found that the proportions of leaks in the nose and nose\chin categories were significantly higher than the null value ($p < 0.0001$).[17] The leak site distributions for males and females were similar and were also significantly different from the null.[17] About 79% of all subjects had faceseal leaks at the nose or multiple leaks which included the nose. About 51% had leaks at the chin or multiple leaks which included the chin, while only about 19% had leaks at the cheek or multiple leaks which included the cheek.

Observed leak shapes are summarized in Table III. A total of 110 leaks were observed on 73 subjects. Independence of multiple leaks on the same subject was confirmed by Fisher's exact test.[17] The one-sample binomial test found the observed

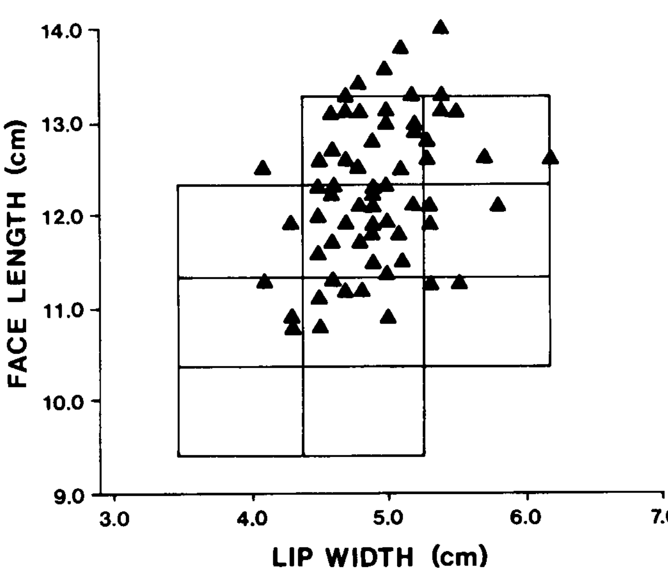


Figure 2—Distribution of test subjects on the fit test panel

proportion (0.727) of diffuse leaks for all subjects was significantly greater than 0.5 ($p < 0.0001$).[17] The proportion of diffuse leaks for males was 0.822 and for females was 0.630. These proportions were significantly different by the chi-square test for independence,[17] and only the proportion of diffuse leaks for males was significantly different from the null ($p < 0.0001$).[17]

To determine the association of leak sites and facial dimensions, subsets of subjects with a common leak type(s) were formed. All of the subjects without the leak site(s) of interest were combined to form comparison subsets. Because of small numbers, some subsets were not tested, and only nonparametric tests could be performed on others. The leak site subsets tested are listed in Table IV.

A subset of subjects with airflow streamlining was added to the faceseal leak site categories. Streamlining was hypothesized by Myers et al.[7] as being the cause of the bias which they had identified in their mannequin study of in-facepiece sampling factors. Visual evidence of streamlining was found from aerosol deposition patterns on 16 subjects in this study. These patterns originated at the faceseal leak site and followed relatively straight lines to the subjects' noses or mouths. Subjects with these patterns were treated as a separate subset because of the implications of this phenomenon on the validity of in-facepiece sampling for the determination of fit factors.

The means for each facial dimension of subjects in a leak site subset were compared to the mean of the comparison subset using a Student's t-test or Wilcoxin's Rank Sum Test.[17] In addition a two-way ANOVA was performed for each dimension using gender, leak site, and their interactions as the independent variables, and facial dimension as the dependent variable.[17] By

TABLE II
Observed Respirator Leak Sites for All Subjects and Gender Subsets

Leak Site	All Subjects (%)	Gender Male (%)	Gender Female (%)
Nose	24 (32.9)	13 (33.3)	11 (32.4)
Cheek	6 (8.2)	4 (10.2)	2 (5.9)
Chin	6 (8.2)	3 (7.7)	3 (8.8)
Nose and cheek	4 (5.5)	3 (7.7)	1 (2.9)
Nose and chin	26 (35.6)	11 (28.2)	15 (44.1)
Cheek and chin	1 (1.4)	1 (2.6)	0 (0.0)
Nose, cheek, and chin	4 (5.5)	2 (5.1)	2 (5.9)
None detected	2 (2.7)	2 (5.1)	0 (0.0)
Total	73	39	34

TABLE III
Observed Leak Site Shapes

Subset	Leak Shape Point (%)	Leak Shape Diffuse (%)	Total
All subjects	30 (27.3)	80 (72.7)	110
Male	10 (17.8)	46 (82.2)	56
Female	20 (37.0)	34 (63.0)	54
Black	2 (18.2)	9 (81.8)	11
Asian	3 (23.1)	10 (76.9)	13
White	24 (30.0)	56 (70.0)	80
Other	1 (16.7)	5 (83.3)	6

deduction, it was assumed that a difference in a dimension was attributed to gender if a significant difference was found in the two-sample test but not in the two-way ANOVA. The results of these analysis are shown in Table V.

Because of small sample numbers, race was not included in the analysis. However, an extended Fisher's exact test found that race distributions were not significantly different for any of the comparison subsets.[21] Therefore, it was assumed that race would not affect the outcome of the two-sample tests or the two-way ANOVA.

Measured fit factors were recorded for each subject as part of the quantitative fit test and exposure to the fluorescent aerosol. Observed values ranged from 21 to greater than 50 000 with a geometric mean of 4410. The distribution of these values was found to be log normal by the Kolmogorov-Smirnov one-sample test.[17] However, interpretation of these data are conditional because of the possibility of bias in fit factor measurements caused by aerodynamic streamlining identified by Myers et al.[7] and the evidence of that phenomenon observed on some subjects in this study.

The significance of differences between fit factor geometric means of various subsets and their comparison groups were tested by appropriate two-sample tests.[17] Results of these comparisons are shown in Table VI. The geometric means of fit factors for the chin leak only ($p = 0.007$) and nose/chin leaks ($p = 0.015$) were significantly lower than their comparison subsets. This would indicate that aerosol penetration through chin leaks is much greater than through leaks at other sites. These results are similar to those found in a study of particle size-dependent losses at leak sites.[22]

The association of each facial dimension and fit factor was measured by Pearson's or Spearman's correlation coefficients.[17] Those results are summarized in Table VII. It is noted that no significant correlations were found for the dimensions used to define the Los Alamos respirator test panel.[12]

TABLE IV
Leak Site Subsets Tested for Differences in Facial Dimensions

Test Subset	Leak Sites Included in the Subsets	Number of Subjects
Nose leaks only	nose	24
All nose leaks	nose nose-cheek nose-chin	56
Cheek leaks only	cheek	6
All cheek leaks	cheek nose-cheek cheek-chin	15
Chin leaks only	chin	6
All chin leaks	chin nose-chin cheek-chin	37
Nose-chin leaks	nose-chin	26
Streamlining	subjects with airflow streamlining	16

TABLE V
Significant Differences between Facial Dimensions of Leak Site Subsets and Comparison Subsets

Dimension	Nose Leaks Only	All Cheek Leaks	All Chin Leaks	Nose-Chin Leaks	Stream/lining Leaks
Biectoorbitale breadth			B, D		B, D
Bizygomatic breadth			B, D	B, D	B, D
Bigonial breadth		A, C		B, D	B, D
Menton-nasion length (face length)		B, C			B, D
Menton-subnasale length					B, D
Subnasale-nasion length		A, C			
Biocular breadth					B, D
Nasal root breadth					B, D
Nose width	A, C		A, D	B, D	B, D
Lip width					
Bitragion-menton arc		B, C		A, D	B, D
Bitragion-subnasale arc		B, C		A, D	A, D

[A]Significant difference for all subjects in the test group
[B]Significant difference for subjects in the test group affected by gender
[C]Dimension in the test group was significantly larger than the comparison group.
[D]Dimension in the test group was significantly smaller than the comparison group.

DISCUSSION

The results of this study indicate that faceseal leaks at the nose and chin are of the greatest importance in affecting leakage on this type of half-mask respirator. Leaks at these sites or multiple leaks which included these sites accounted for 89% of all the observed leaks. Also, fit factors for nose/chin and all chin subsets were found to be significantly lower than their comparison subsets. Therefore, leaks at these sites would be most likely to

TABLE VI
Fit Factor Geometric Means of Leak Site Subsets

Subset	Number Subset	Subset Geometric Mean	Comparison Subset Geometric Mean	t-test p value
Nose leaks only	24	5210	2360	0.066
All nose leaks	58	2640	5460	0.148
Nose/chin leaks	26	1590	4400	0.015[A]
Cheek leaks only	6	4020	2980	0.659
All cheek leaks	15	2830	2830	0.998
Chin leaks only	6	2930	3080	0.950
All chin leaks	37	1810	4580	0.019[A]
Streamlining leaks	15	1410	3810	0.148

[A]Significantly different at $\alpha = 0.05$

TABLE VII
Facial Dimensions with Significant Correlation Coefficients to Fit Factors

Facial Dimension	All Subjects	Males	Females	Nose Leaks Only	All Nose Leaks	All Chin Leaks
Menton-subnasale length	0.322	0.431			0.290	0.361
Biocular breadth	0.234				0.250	
Nasal root breadth	0.285		0.336	0.467	0.306	

occur and would result in the greatest penetration of contaminant into the facepiece.

The distributions of leak sites for males and females were similar, but females were found to have significantly fewer diffuse leaks. About 71% of the significant differences in facial dimensions for leak site subsets were attributed to gender. A previous study also found proportional differences by gender in facial dimensions within respirator test panel cells.[23] Anthropological definition of the female head and face is as much by shape as by size.[24] This would indicate that respirators designed for male faces may not fit females in the same way, even when selected on the basis of facial dimensions.

Of the two dimensions used to define respirator test panels (face length and lip width), only face length was found to be significantly different in two leak site subsets. No significant differences between geometric means of fit factors for these subsets and their comparison groups were found. In addition, there was no correlation between these dimensions and fit factors. These results are in agreement with previous studies which failed to indicate an association between respirator leakage and these dimensions.[14,15] This would imply that face length and lip width alone may not be good criteria for selecting respirators or predicting respirator leakage.

The prevalence of nose leaks observed in this study (78%) followed the limited observations of two previous studies which identified faceseal leak sites by other methods.[25,26] In addition, nose dimensions (subnasale-nasion length, nasal root breadth, and nose width) comprised 25% of the significant associations of facial dimension to leak site category. Nasal root breadth also had significant correlation coefficients with fit factors for four groups of subjects. These results would indicate that consideration should be made for including a nasal dimension in respirator test panels and in the sizing and selection of respirators for individual wearers.

Based on observed deposition patterns, diffuse leaks were considered to approximate slits and point leaks to approximate round holes. These shapes would have implications on the leak flow equations used in respirator leak models[3-6] and pressure decay through faceseal leaks.[9] Because of the high prevalence (73%) of diffuse leaks, appropriate equations may be those that represent flow through slits rather than through round holes.

A significant observation in this study was the presence of very heavy aerosol deposition along airflow streamline patterns on about 22% of the subjects tested. These observations confirm the hypothesis of this phenomenon in a study of bias in the measurement of fit factors.[7]

Certain conditions known to affect the faceseal leakage of respirators were not addressed in this study. They limit conclusions which can be made from this study and should be addressed in further research. These conditions are (1) different brands and models of half-mask respirators, (2) intrasubject leak variability, and (3) subject breathing rates at higher work rates.

ACKNOWLEDGMENT

The authors would like to thank Dr. J.T. McConville and his associates at Anthropology Research Projects, Inc., for their advice in the selection of facial dimensions and training in making anthropometric measurements.

REFERENCES

1. "Notice of Proposed Rulemaking: NIOSH Revision of Tests and Requirements for Certification of Permissibility of Respiratory Protection Devices used in Mines and Mining" *Federal Register* 52 (27 August 1987). p. 32416.
2. **Oestenstad, R.K., J.L. Perkins, and V.E. Rose:** Identification of Faceseal Leak Sites on a Half-Mask Respirator. *Am. Ind. Hyg. Assoc. J. 51*:000-000 (1990).
3. **Williams, F.T.:** An Analytical Method for Respirator Performance Prediction Utilizing the Quantitative Fit Test. *J. Int. Soc. Respir. Prot. 1*:109-125 (1983).
4. **Cooper, D.C., W.C. Hinds, and J.M. Price:** Common Materials for Emergency Respiratory Protection: Leakage Tests with a Mannequin. *Am. Ind. Hyg. Assoc. J. 44*:720-726 (1983).
5. **Campbell, D.L.:** The Theoretical Effect of Filter Resistance and Filter Penetration on Respirator Protection Factors. *J. Int. Soc. Respir. Prot. 2*:198-204 (1984).
6. **Hinds, W.C. and P. Bellin:** Performance of Dust Respirators with Facial Seal Leaks. II: Predictive Model. *Am. Ind. Hyg. Assoc. J. 48*:842-847 (1987).
7. **Myers, W.R., J. Allender, R. Plummer, and T. Stobbe:** Parameters that Bias the Measurement of Airborne Concentration within a Respirator. *Am. Ind. Hyg. Assoc. J. 47*:106-114 (1986).
8. **Hinds, W.C. and G. Kraske:** Performance of Dust Respirators with Facial Seal Leaks. I: Experimental. *Am. Ind. Hyg. Assoc. J. 48*:836-841 (1987).
9. **Carpenter, D.R. and K. Willeke:** Noninvasive, Quantitative Respirator Fit Testing through Dynamic Pressure Measurement. *Appl. Ind. Hyg. 3*:485-491 (1988).
10. **National Institute for Occupational Safety and Health:** *Anthropometry for Respirator Sizing* by J.T. McConville, E. Churchill, and L.L. Laubach (DHEW/NIOSH TR-004-73). Cincinnati, Ohio: National Institute for Occupational Safety and Health, 1972. pp. 1-44.
11. **Hyatt, E.C., J.A. Pritchard, and C.P. Richards:** Respirator Efficiency Measurements Using Quantitative DOP Man Tests. *Am. Ind. Hyg. Assoc. J. 33*:635-643 (1972).
12. **Los Alamos National Laboratory:** *Selection of Respirator Test Panels Representative of U.S. Adult Sizes* by A. Hack, E.C. Hyatt, B.J. Held, T.O. Moore, C.P. Richards, and J.T. McConville (LASL Report LA-5488). Los Alamos, N. Mex.: Los Alamos Scientific Laboratory of the University of California, 1974.

13. **Los Alamos National Laboratory:** *Respirator Protection Factors* by E.C. Hyatt (LASL Report LA-6084-MS). Los Alamos, N. Mex.: Los Alamos Scientific Laboratories of the University of California, 1976.
14. **Liau, Y.H., A. Bhattacharya, H. Ayer, and C. Miller:** Determination of Critical Anthropometric Parameters for Design of Respirators. *Am. Ind. Hyg. Assoc. J. 43*:897–899 (1982).
15. **Moore, D.E. and T.J. Smith:** Measurement of Protection Factors of Chemical Cartridge, Half-Mask Respirators under Working Conditions in a Copper Smelter. *Am. Ind. Hyg. Assoc. J. 37*:453–458 (1976).
16. **American National Standards Institute:** *American National Standard Practices for Respiratory Protection.* (Z88.2-1980). New York: ANSI, 1980.
17. **Gustafson, T.L.:** *True Epistat.* 2d ed. Richardson, Tex.: Epistat d Services, 1987.
18. **Jamison, P.L. and S.L. Zegura:** A Univariate and Multivariate Examination of Measurement Error in Anthropometry. *Am. J. Phys. Anthropol. 40*:197–204 (1974).
19. **Spielman, R.S., F.J. daRocha, L.R. Weitkamp, R.H. Ward, J.V. Neel, and N.A. Chagnon:** The Genetic Structure of a Tribal Population, the Yanomama Indians, VII. Anthropometric Differences among Yanomama Villages. *Am. J. Phys. Anthropol. 37*:345–356 (1972).
20. **Dixon, W.J.:** *Introduction of Statistical Analysis.* New York: McGraw-Hill, Inc. 1983. p. 314.
21. **Freeman, G.H. and J.H. Halton:** Note on an Exact Treatment of Contingency, Goodness of Fit and Other Problems of Significance. *Biometrika. 38*:141–149 (1951).
22. **Holton, P.M., D.L. Tackett, and K. Willeke:** Particle Size-Dependent Leakage and Losses of Aerosols in Respirators. *Am. Ind. Hyg. Assoc. J. 48*:848–854 (1987).
23. **Johnson, B.A.:** "Gender Differences Affecting Respirator Mask Sizing Systems." Paper presented at the American Society of Safety Engineers Professional Development Conference, Baltimore, Md., June 1987.
24. **National Institute for Occupational Safety and Health:** *Human Variability and Respirator Sizing* by J.T. McConville and E. Churchill (DHEW/NIOSH Pub. No. 76-146). Cincinnati, Ohio: National Institute for Occupational Safety and Health, 1976. pp. 1–53.
25. **Adley, F.E. and D.E. Wisehart:** Methods for Performance Testing of Respiratory Protective Equipment. *Am. Ind. Hyg. Assoc. J. 23*:251–256 (1962).
26. **Cohen, H.J.:** Determining and Validating the Adequacy of Air-Purifying Respirators Used in Industry. Part II: Development of a New Respirator Fit Test. *J. Int. Soc. Respir. Prot. 2*:305–312 (1984).