DISTRIBUTION OF FACESEAL LEAK SITES ON HALF-MASK RESPIRATORS AND THEIR ASSOCIATION WITH FACIAL DIMENSIONS*

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Faceseal leaks on one brand of half-mask respirator worn by 73 human subjects wearing were identified by deposition of a fluorescent tracer aerosol during a standard quantitative fit test. The identified leaks were categorized according to their facial location and shape. The distributions of those categories were determined and the association of anthropometric facial dimensions with leak sites were tested. It was found that about 79% of all observed leaks occurred at the nose or were multiple leaks which included the nose. About 73% of all leaks approximated the shape of a slit rather than a round orifice. Males were much more likely to have slit-like leaks than females. Significant associations were found for 25% of the tests between facial dimensions

and leak site subsets. Only two significant associations were found for the facial dimensions used to define the Los Alamos respirator test panel. Gender was a factor in many of the significant associations. The amount of leakage through chin leaks was found to be higher than leaks at other sites. Significant correlation of facial dimensions and fit factor was found for three facial dimensions; none of which are used to define the respirator test panel. Evidence of air flow streamlining within the facepiece was observed on 22% of the subjects. This study indicates that gender is a factor in how a respirator fits, and that other facial dimensions should be considered in defining a respirator test panel and selecting a respirator for an individual wearer.

INTRODUCTION

While there has been extensive work conducted to quantify respirator leakage, very little has been reported on the size and shape of respirator 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 NIOSH has proposed to include the use of facial dimensions 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.

Recently, several models to predict respirator leakage have been developed.[2,3,4,5] In these models, protection factors are predicted by the ratio of total air flow into the respirator faceplece to air flow through faceseal leaks. In general, air flow 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 some studies.[6,7,8] A study using capillaries as artificial leaks found these models to be accurate within the restrictions of assumptions about values of the coefficient and exponent for laminar flow.[6]

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 *vs*. 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. They noted also that flow rate was strongly influenced by leak size, being 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 air flow through round leaks.[9] In this study, the size of respirator leaks is predicted from the respirator cavity volume and the rate of pressure decay. Air flow into the facepiece is then determined from flow equations using the same coefficients and exponents used in leak models. The authors 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 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]

The relationship between these facial dimensions and respirator fit was accepted but never validated by association with respirator leakage. The association of these dimensions with protection factors was tested, and a significant correlation for lip width ($p = 0.30$) was found but not for face length.[14] However, the correlation coefficient was relatively low (0.22), 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 ($n = 9$).

MATERIALS AND METHODS

The purpose of this study was to determine the distribution of faceseal leak sites 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. Each subject was tested one time according to a protocol developed to identify leaks by the deposition of a fluorescent tracer aerosol at the leak site.(16) The test protocol included: 1) measurement of facial dimensions, 2) pre-exposure photograph, 3) fitting with a respirator and pressure check, 4) performing a quantitative fit test according to an ANSI recommended method,(17) and 5) post-exposure photographs and classification of 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. The faceplece size was selected for each subject according to their face length and lip width. 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 protection factor greater than 10 were not used in the study.

The facial dimensions illustrated in Figure 1 were measured with sliding and spreading calipers and 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. The purpose of these measurements was to develop experience in locating facial landmarks and making measurements, and to determine the reliability of the investigator's measurement techniques.

Data for each dimension were analyzed by a two-way analysis of variance (two-way ANOVA).[18] As expected, the between-subject variation was significant for all dimensions. There was also significant between-test variation for biectoorbitale breadth ($p = 0.049$), subnasale-nasion length ($p = 0.013$), and lip width ($p = 0.042$). A graph of the residuals for these dimensions indicated that, in each case, one subject had observations which deviated from the mean more than any of the other subjects. These results were considered adequate relative to expected inter-observation variability identified in anthropological studies.[19,20]

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.[18]

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 included respirator size, subject demographic information, facial dimensions, quantitative fit test results, and leak site and shape classifications. Data were entered into a spreadsheet, and appropriate parametric and nonparametric statistical analysis performed using True Epistat Statistical Software.[18] 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 $i = 1,2,\cdots,8$).[21] With 73 subjects, a minimun difference of 0.115 could be detected between the null proportion and an observed proportion of one type of leak shape at an alpha value of 0.05 and a power of 0.85. Given that a leak occurred, leak shape was a dichotomous variable whose distribution was assumed to be binomial.

RESULTS

Subjects included university students, staff and faculty who volunteered to participate in the study. Their average age was 30.6 years, and ranged from 21 to 50. Ten 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 right 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. It is very obvious that, for all subjects, the leak categories with the highest proportions were those at the nose and those which were multiple leaks involving the nose and chin. The chi-square goodness-of-fit test verified that all categories were not equally likely to occur ($p < 0.0001$).[18] Frequencies for all other categories were less than their expected values. About 79% of all subjects tested had leaks at the nose or multiple leaks which included the nose. Approximately 51% of the subjects had leaks at the chin or multiple leaks that included the chin. Only about 19% of the subjects had leaks at the cheek or multiple leaks which included the cheek.

The leak site distributions for males and females also were tested by the chi-square goodness-of-fit test.[18] As in the overall results, significant differences existed in the categories of nose leaks and nose\chin leaks. Male and female leak site distributions also were compared to each other using an extended Fisher's exact test and were found not to be significantly different.[22]

Observed leak shapes are summarized in Table III. A total of 110 leaks were observed on 73 subjects. When more than one leak occurred on the same subject, the shape of one was found to be independent of the other leak by Fisher's exact test ($p = 1.000$).[18] For all subjects, it was found that the proportion of diffuse leaks (0.727) was significantly greater than 0.5 by the one-sample binomial test ($p < 0.0001$).[18] The proportion of diffuse leaks for males was 0.822 and for females was 0.630. However, only the observed proportion of diffuse leaks on males was significantly different than 0.5 ($p < 0.0001$). A chi-square test for independence found that that males were significantly more likely to have diffuse leaks than females ($p = 0.041$).[18]

Subsets were formed of subjects with a primary leak type in common. 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 limited tests could be performed on others. The leak site subsets tested are listed in Table IV.

A subset of subjects with air flow streamlining was added to the faceseal leak site categories. Streamlining was hypothesized by Myers *et al*. as being the cause of the bias which they had identified in their mannequin study of in-facepiece sampling factors.[7] Visual evidence of streamlining was found from aerosol deposition patterns on 16 subjects in this study (13 females and 3 males). All but one of the streamlining leaks were nose leaks. 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 all other subjects using a Student's t-test[18] or Wilcoxin's Rank Sum Test.[18] 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.[18] By 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.[22] Therefore, it was assumed that race would not affect the outcome of the two-sample tests or the two-way ANOVA.

In summary, only nose width was found to be significantly different in the comparisons of the single leak subsets of nose only, cheek only, and chin only. Nose width was found to be significantly different in four of the eight comparisons. Significant differences in three sets of comparisons were found for biectoorbitale breadth, bizygomatic breadth, bigonial breadth, bitragion-menton arc, and bitragion-subnasale arc. Only two significant differences were observed for the two dimensions used to define the Los Alamos respirator test panel.[12] Face length (menton-nasion length) was found to be significant in only two comparisons, and lip width was not significant in any of the comparisons.

Of the 24 significant differences observed, 17 were attributed to differences in gender. These results would indicate that gender is an important factor in the location of respirator leak sites. In most cases, the significant dimension was smaller thus indicating the difference was related to female dimensions.

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 3060. The distribution of these values was found to be log-normal by the Kolmogorov-Smirnov one-sample test.(18) These data indicate that the subjects were able to obtain exceptionally good faceseals and in all cases the values exceeded the assigned fit factor of 10.(23) However, interpretation of these data are conditional because of the possibility of bias in fit factor measurements due to 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 groups were tested by Student's t-test.(18) There were differences between the geometric means for males and females, subjects with point leaks and those with diffuse leaks, and subjects with air flow streamlining and those without, but none were significant.

Results of comparisons of mean fit factors for subjects in the various leak site subsets are shown in Table VI. The geometric means for the chin leaks only and nose/chin leaks 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.[24]

The association of each facial dimension and fit factor was measured by Pearson's or Spearman's correlation coefficients.[18] Coefficients were calculated for all subjects, by gender, for subjects with air flow streamlining, and for all of the leak site subsets. Coefficients which were significantly different from 0.0 were found in only six groups. Those results are summarized in Table VII. Menton-subnasale length and nasal root breadth were found to have significant coefficients in four groups. It is noted that no significant correlations were found for the dimensions used to define the Los Alamos respirator test panel.[12]

DISCUSSION

Results of this study indicate that about 79% of all subjects wearing one brand of half-mask respirator had faceseal leaks at the nose or multiple leaks which included the nose. About 51% of all the subjects tested 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. The distribution of leak sites on male and female subjects were not significantly different. Approximately 73% of leaks on all subjects were diffuse, although females were found to have a significantly smaller proportion of diffuse leaks than males (63% vs. 82%).

The association of the 12 measured facial dimensions with eight leak site subsets were also tested. Statistically significant associations were found in 24 of the 96 tests. Of these dimensions, 75%

were smaller than their comparison groups. About 71% of the significant differences were attributed to differences in gender. About 58% of the dimensions with significant association were face width measurements, about 17% were face length measurements, and about 17% were arc measurements.

Of the two dimensions used to define respirator test panels (face length and lip width) only face length was significantly associated with two leak site subsets. This indicates that these dimensions may not be good criteria for selecting respirators or predicting respirator leakage. Previous studies also failed to indicate an association between respirator leakage and these dimensions.[14,15]

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 nasal dimensions should be considered in defining 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,[2,3,4,5] and the pressure decay through faceseal leaks.[9] Due to the high prevalence (73%) of diffuse leaks, appropriate equations may be those that represent flow through slits rather than round holes.

A significant observation in this study was the presence of very heavy aerosol deposition along air flow streamline patterns on about 22% of the subjects tested. All of these patterns originated from point leaks and followed a relatively straight line to the subjects' nostril or mouth, and all but one were nose leaks. It is not known if streamlining does not occur with diffuse leaks or, if it does, that the test was not sensitive enough to detect it. Subjects with streamlining leaks were significantly smaller in 10 of the 12 facial dimensions measured, and 81% were female. Streamlining was hypothesized as causing bias in the measurement of fit factors in laboratory mannequin studies.(7) This study confirms that this phenomenon occurs on human subjects.

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

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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*	4	1	5
Total	39	34	73

*The race category of "Other" included Hispanics and Asian Indians.

TABLE II

Observed Respirator Leak Sites for All Subjects

and Gender Subsets

Leak Site	All Subjects	(%)	Gender: Male	(%)	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 & Cheek	4	(5.5)	3	(7.7)	1	(2.9)
Nose & Chin	26	(35.6)	11	(28.2)	15	(44.1)
Cheek & Chin	1	(1.4)	1	(2.6)	0	(0.0)
Nose, Cheek & 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	(%)	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
Oriental	3	(23.1)	10	(76.9)	13
White	24	(30.0)	56	(70.0)	80
Other	1	(16.7)	5	(83.3)	6

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 Aerodynamic Streamlining	16

TABLE V

Facial Dimensions with Significant Association with Leak Sites

Dimension	Nose Leaks Only	All Nose Leaks	Cheek Leaks Only	All Cheek Leaks	Chin Leaks Only	All Chin Leaks	Nose-Chin Leaks	Stream-lining Leaks
Biectoorbitale Breadth						G[2]		G[2]
Bizygomatic Breadth						G[2]	G[2]	G[2]
Bigonial Breadth				A[1]			G[2]	G[2]
Menton-Nasion Length				G[1]				G[2]
Menton-Subnasale Length								G[2]
Subnasale-Nasion Length				A[1]				
Biocular Breadth								G[2]
Nasal Root Breadth								G[2]
Nose Width	A[1]					A[2]	G[2]	G[2]
Lip Width								
Bitragion-Menton Arc				G[1]			A[2]	G[2]
Bitragion-Subnasale Arc				G[1]			A[2]	A[2]

A - Significant difference for all subjects in the test group.

G - Significant difference for subjects in the test group affected by gender.

[1]Dimension in the test group was significantly larger than the comparison group.

[2]Dimension in the test group was significantly smaller than the comparison group.

TABLE VI

Fit Factor Geometric Means of Leak Site Subsets

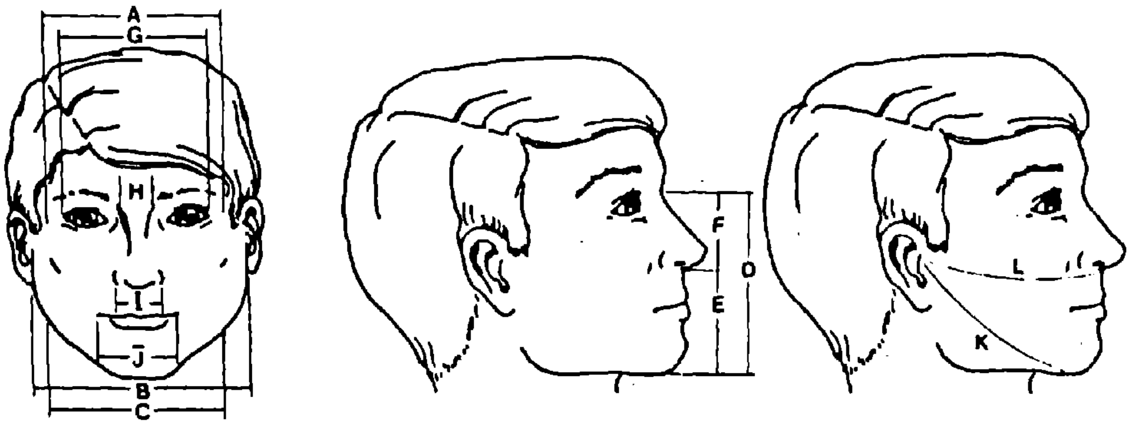
Subset	Number in Subset	Subset Geometric Mean	Comparison Subset Geometric Mean	t-test p value
Nose Leaks Only	24	5210	2360	0.066
All Nose Leaks	58	2640	5460	0.148
Nose/Chin Leaks	26	1590	4400	0.015*
Cheek Leaks Only	6	4020	2980	0.659
All Cheek Leaks	15	2830	2830	0.998
Chin Leaks Only	6	2930	3080	0.950
All Chin Leaks	37	1810	4580	0.019*
Streamlining Leaks	15	1410	3810	0.148

* 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	



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.

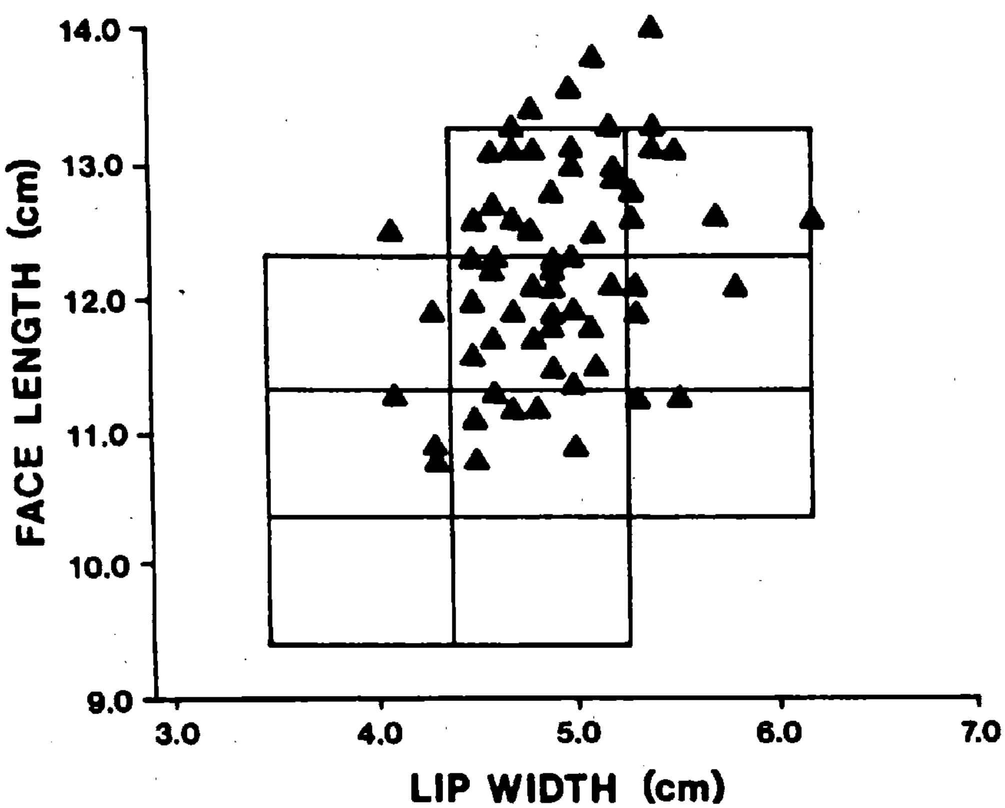


Figure 2 — Distribution of test subjects on the fit test panel.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

By using deposition of a fluorescent tracer aerosol during a standard quantitative fit test, faceseal leaks on one brand of half mask respirator worn by 73 human subjects were identified. The leaks were categorized according to their facial location and shape. The distributions of those categories were determined and the association of anthropometric facial dimensions with leak sites were tested. It was found that about 79 percent of all observed leaks occurred at the nose or were multiple leaks which included the nose. About 73 percent of all leaks approximated the shape of a slit rather than a round orifice. Males were much more likely to have slit like leaks than females. Significant associations were found for 25 percent of the tests between facial dimensions and leak site subsets. Only two significant associations were found for the facial dimensions used to define the Los Alamos respirator test panel. Gender was a factor in many of the significant associations. The amount of leakage through the chin area was higher than leaks at other sites. Significant correlation of facial dimensions and fit factor was found for three facial dimensions, none of which are used to define the respirator test panel. Evidence of air flow streamlining within the facepiece was noted on 22 percent of the subjects.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms NIOSH-Publication, NIOSH-Grant, Grant-Number-R03-OH-02580, End-Date-03-31-1989, Respirators, Personal-protective-equipment, Respiratory-protective-equipment, Respiratory-equipment

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
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