Ann. Occup. Hyg., Vol. 53, No. 3, pp. 297–305, 2009

doi:10.1093/annhyg/men089

New Respirator Fit Test Panels Representing the Current Chinese Civilian Workers

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Received 6 September 2008; in final form 15 December 2008; published online 27 February 2009

Respirator fit test panels provide an objective tool for selecting representative human test subjects based upon their facial characteristics for use in research, product development, testing and certification. Fit test panels were typically based upon anthropometric data such as the 1967–1968 survey of American military personnel. In this study, the objectives were to: (i) evaluate the applicability of the recently developed National Institute for Occupational Safety and Health (NIOSH) respirator fit test panels for Chinese workers and (ii) develop new respirator fit test panels using the Chinese survey data. Overall, 95% of the workers in the Chinese survey fall within the NIOSH bivariate and principal component analysis (PCA) panels, suggesting that these panels would also be appropriate for the Chinese population. However, distribution of the subject across the panels was not uniform; only 6.3% of survey participants fell into five cells of the bivariate panel and only 7.2% were found within three cells of the PCA panel. Therefore, new respirator fit test panels with subject dimensions and distributions specific to Chinese workers may be beneficial for certain applications. Two new respirator fit test panels were developed with the same techniques used to create the NIOSH panels. All measurements were weighted to match age and gender distributions of the Chinese population from the 2005 census. The bivariate approach used face length and face width measurements, and the PCA panel was developed using the first two principal components obtained from a set of 10 facial dimensions. Respirators designed to fit these Chinese worker-specific panels are also likely to accommodate >95% of Chinese workers.

Keywords: civilian workers; fit test panels; respirators; respirator sizing

INTRODUCTION

Respirator fit test panels provide an objective tool for selecting representative human test subjects based upon their facial characteristics for use in research, product development, testing and certification. In the early 1970s, the National Institute for Occupational Safety and Health (NIOSH) asked the Respirator Research and Development Section of Los Alamos National Laboratory (LANL) to develop anthropometric specifications for full- and half-facepiece respirator fit testing. Specifications were based on US Air Force (USAF) anthropometric surveys conducted in 1967 and 1968 (Clauser *et al.*, 1972; Kennedy, 1986). The full-facepiece fit test panels are based on the bivariate distribution of face length and face width, and the half-facepiece fit test panels are based on the bivariate distribution of the face length and lip length (Hack *et al.*, 1973; Hack and McConville, 1978). The LANL fit test panels design specifications, including the upper and lower limit criteria for each dimension, have been

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previously published (Hack *et al.*, 1973; Hack and McConville 1978).

There has long been concern about the applicability of respirator fit test panels generated from military personnel, for civilian workers. In 2003, a large-scale head-and-face anthropometric survey of US respirator users was conducted by NIOSH (Zhuang *et al.*, 2004; Zhuang and Bradtmiller, 2005). In these studies, the researchers compared military and civilian head-and-face measurements and found that the LANL full-facepiece panel excluded >15% of the current US population. The 2003 data were used to develop the new fit test panels (Zhuang *et al.*, 2007). A bivariate fit test panel was developed using face length and face width data weighted to match the age and race distribution of the US population as determined from the 2000 census. A principal component analysis (PCA)-based panel was developed using the first two principal components (PCs) obtained from a set of 10 weighted facial dimensions. These 10 dimensions were selected because they previously were shown to be associated with respirator fit and leakage and can predict other commonly measured face dimensions well (Zhuang *et al.*, 2005, 2007). Respirators designed to fit these panels are expected to accommodate >95% of the current US civilian workers. Both panels are more representative of the US population than the existing LANL panel and are appropriate for testing and research on both half-mask and full-facepiece respirators. Recent work by Zhuang *et al.* (2008) support the selection of the facial dimensions used for developing the new NIOSH bivariate respirator fit test panel.

Current Chinese respirator certification standards follow European guidelines, requiring a total inward leakage test on 10 subjects, while Chinese respirator manufacturers base their respirator designs on LANL fit test panels (Yang *et al.*, 2007). Even though anthropometric data have been collected from Chinese military and civilian populations (CNIS, 1981, 1988, 1998), respirator fit test panels for Chinese respirator users have yet to be established (Yang *et al.*, 2007). Yang *et al.* collected facial anthropometric data on 451 Chinese university students and teachers and compared their dimensions to the LANL fit test panels (2007). In total, 12–35% of the subjects fell outside the ranges of the LANL fit test panels because Chinese adults had shorter and wider facial characteristics than USAF personnel. However, the sample size was small and may not be representative of Chinese civilian workers or respirator users.

In response to needs for new anthropometric data for Chinese workers, a large-scale head-and-face anthropometric survey of 3000 Chinese civilian respirator users was conducted in 2006 (Du *et al.*, 2008). Through comparison with the facial dimensions of American subjects, that study found that Chinese civilian adults have shorter face length and nose protrusion and larger face width and lip length.

In this study, the objectives were to: (i) evaluate the applicability of the recently developed NIOSH respirator fit test panels for Chinese workers and (ii) develop new respirator fit test panels using the Chinese survey data.

METHODS AND MATERIALS

Chinese anthropometric database

In 2006, a nationwide anthropometric survey of respirator users was conducted across China (Du *et al.*, 2008). The subjects were recruited from various industries, including manufacturing, construction, health care, mining and others. These workers often rely on respirators to prevent work-related respiratory illnesses and injuries. A stratified sampling plan was used with an equal sample size in each stratum. The survey consisted of three age strata (18–29, 30–44 and 45–66 years) and two gender strata (male and female). Height, weight, 19 face dimensions and neck circumference were collected from 3000 subjects (2026 males and 974 females) using traditional measurement techniques.

The sampling strategy called for equal representation in each of the sampling cells to adequately capture that the anthropometric variability in all segments of the population. Information regarding the survey was provided to numerous worksites and individuals volunteered to participate. Anyone who volunteered for the study was measured in an effort to collect an adequate sample for each stratum. However, subjects in the work force did not fall into those cells in equal proportion. Therefore, the sample needed to be weighted to accurately represent Chinese civilian workers. Since demographic statistics were not available for the respirator-wearing population, the proportionality was weighted based on age and gender information from the China 2005 census. A detailed discussion of calculating weighting factors can be found elsewhere (Zhuang and Bradtmiller, 2005).

Bivariate distribution approach

The bivariate distribution approach was used originally by LANL to develop respirator fit test panels. It was determined previously that the LANL panel for full-facepiece respirator fit tests is no longer adequate for the US civilian population (Zhuang and Bradtmiller, 2005). Even though the use of the LANL panels is a common practice for respirator design in China, at least 12% of one study population involving 461 university students and teachers did not fit within the half-mask and full-facepiece panels (Yang *et al.*, 2007). Since the population for which the LANL panels were developed might no longer be representative, it is imperative that respirator fit test panels be generated to be inclusive of the Chinese worker population. The procedures used by NIOSH for developing a representative bivariate respirator fit test panel were implemented in this study (Zhuang *et al.*, 2007).

Like the NIOSH bivariate panel, the new Chinese bivariate panel was also divided into 10-cell categories. The suggested number of subjects remained at 25 subjects, and at least two subjects for each cell are specified. Then the number of subjects to be sampled from each cell was determined by matching the percentage of subjects in each cell to the distribution of the Chinese workers.

PCA approach

PCA defines a new coordinate system using linear combinations of the original variables to describe trends in the data. The process for selecting the variables (facial measurements) to include in the PCA calculations was the same as those used by NIOSH previously (Zhuang *et al.*, 2007). The PRINCOMP procedure (SAS Institute Inc., Cary, NC) was then used to perform the PCA and create eigenvalues and eigenvectors using the 3000 subjects in the survey with usable data. The weighting factors were used by using a WEIGHT statement in the SAS PRINCOMP procedure.

The scores from the PCs were used to develop the PCA panel. The panel was divided into eight-cell categories. The number of subjects remained at 25, and at least two subjects for each cell were specified. The number of subjects to be sampled from each cell was determined by matching the percentage of subjects in each cell to the distribution of the Chinese civilian work force.

Using the justification provided by Zhuang *et al.*, 10 dimensions (facial measurements) were included in the PCA, based on four criteria (2007): (i) relevance to respirator fit (based upon literature surveys and expert opinions), (ii) variability analysis, (iii) burden on test subjects and (iv) correlation analysis. Existing data for the first three criteria were described previously in the NIOSH paper (Zhuang *et al.*, 2007) and were used in this study without further analysis. The correlation analysis was performed using the data from the 2006 Chinese survey. The rationale for this criterion was that dimensions excluded from the PCA calculations must have good correlation with and can be predicted by those dimensions that were included in the PCA. Based upon the four criteria, the same 10 facial dimensions used for the NIOSH panels (minimum frontal breadth, face width, bigonial breadth, face length, interpupillary distance, head breadth, nose protrusion, nose breadth, nasal root breadth and subnasale–sellion length) were selected for the Chinese PCA respirator fit test panel. Furthermore, having the same 10 dimensions in the two panels will allow stronger comparisons between the study populations. According to the eigenvectors calculated from the NIOSH data, only the first two PCs were needed to develop the NIOSH PCA panel. Eigenvectors generated from the NIOSH survey data were then used in an algorithm for classifying test subjects into the PCA (Zhuang *et al.*, 2007).

RESULTS

Applicability of NIOSH bivariate and PCA panels for Chinese workers

The Chinese survey data were plotted against the NIOSH bivariate panel as shown in Fig. 1. The NIOSH bivariate fit test panel is based on face length and face width. The distribution of subjects by cell and gender for this panel is summarized in Table 1. The distribution of Chinese subjects in the NIOSH PCA fit test panel is shown in Fig. 2. The distribution of subjects by cell and gender for this panel are summarized in Table 2. Overall, 95% of the workers in the Chinese survey fall within the NIOSH bivariate and

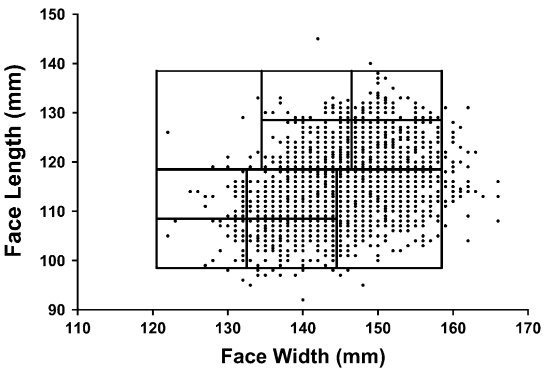

Fig 1. Bivariate distribution is shown along with the NIOSH bivariate panel.

Table 1. Percentage of population and number of Subjects for the NIOSH panel based on face length and face width

Cell	Male (%)	Female (%)	Total (%)
1	0.1	3.7	1.9
2	2.7	30.0	16.3
3	0.2	3.0	1.6
4	15.5	36.3	25.9
5	36.9	17.0	26.9
6	0.1	0.5	0.3
7	9.1	6.1	7.6
8	25.3	1.7	13.4
9	1.0	0.5	0.7
10	3.6	0.1	1.8
Total	94.5	98.9	96.4

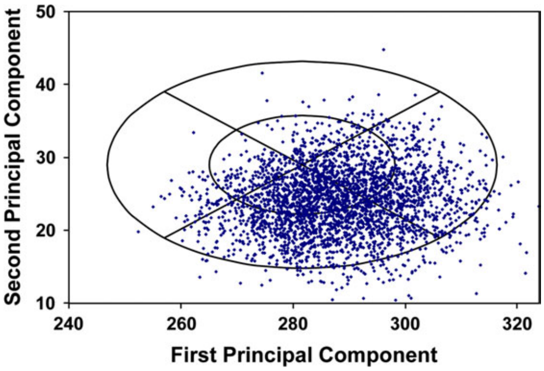

Fig 2. Scatter plot of PCs scores is shown along with the NIOSH PCA panel.

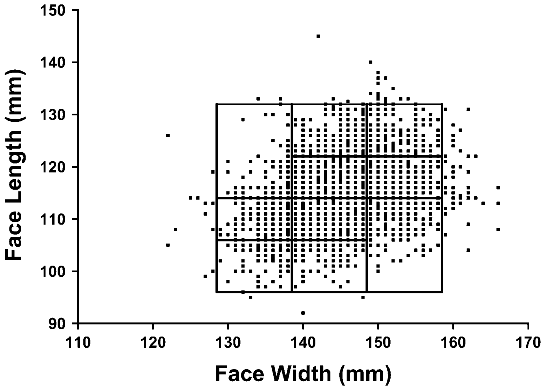

Fig 3. Bivariate distribution is shown along with the Chinese bivariate panel.

Table 2. Percentage of population and number of subjects for the NIOSH panel based on two PCs

Cell	Male (%)	Female (%)	Total (%)
1	0.3	5.8	3.1
2	3	10.1	6.6
3	21.8	46.5	34.2
4	18.1	28.1	23.1
5	4.9	1.3	3.1
6	1.6	0.4	1
7	18.8	3.8	11.3
8	26.3	0.9	13.5
Total	94.8	96.9	95.9

Table 3. Percentage of population and number of subjects for the Chinese panel based on face length and face width

Cell	Male (%)	Female (%)	Total (%)	Male	Female	Total
1	0.2	8.9	4.6	0	2	2
2	1.7	10.3	6.1	0	2	2
3	1.9	19.9	10.9	1	1	2
4	14.2	29.2	21.7	2	3	5
5	10.1	3.1	6.6	2	0	2
6	1.8	9.4	5.6	0	2	2
7	25.1	14.6	19.8	2	2	4
8	17.8	1.0	9.4	2	0	2
9	11.7	1.8	6.7	2	0	2
10	10.9	0.2	5.5	2	0	2
Total	95.4	98.4	96.9	13	12	25

PCA panels, suggesting that if these panels are incorporated into international standards for respiratory protective devices, they would be appropriate for the Chinese population. However, the distribution of subjects across the panels was not uniform; only 6.3% fell into cells 1, 3, 6, 9 and 10 of the bivariate panel and only 7.2% was found within cells 1, 5 and 6 of the PCA panel. Therefore, new test panels with subject dimensions and distributions specific to Chinese workers may be necessary for some applications. In order to get an even distribution of subjects throughout a bivariate panel and a PCA panel, new panels were constructed using data containing only workers from the Chinese population.

Generation of bivariate panel from the Chinese survey data

The layout of cells created for the Chinese population is different from the panel developed by NIOSH in 2007. Cell boundaries were adjusted to distribute the population among the cells as uniformly as possible. The boundaries were set so that at least 95% of the population was included in the panel. Figure 3 shows the scatter plot of the bivariate distribution of Chinese subjects and the boundaries of the new panel based on the Tongji Medical College survey data. This panel covers 95.4 and 98.4% of the male and female civilian work force, respectively (Table 3). Almost 97% of the Chinese subjects are within the boundary of the panel. The distribution of survey subjects within the Chinese bivariate panel is now uniform and each cell contains at least 4.6% of the population. The Chinese bivariate panel has limits of 96.5–132.5 mm for face length and 128.5–158.5 mm for face width (Figure 4). These limits vary from the limits of the NIOSH bivariate panel: 98.5–138.5 mm for face length and 120.5–158.5 mm for face width. Figure 5 shows the boundary conditions for each panel.

Generation of PCA panel from the Chinese survey data

The summary statistics from the PCA weighted to match the Chinese civilian work force are shown in Table 4. The first three PCs explained about 39, 13 and 12% of the total variation, respectively. The fourth PC accounted for only 9%. Zhuang *et al.* used four criteria to determine how many PCs to be retained (2007). A summary of the

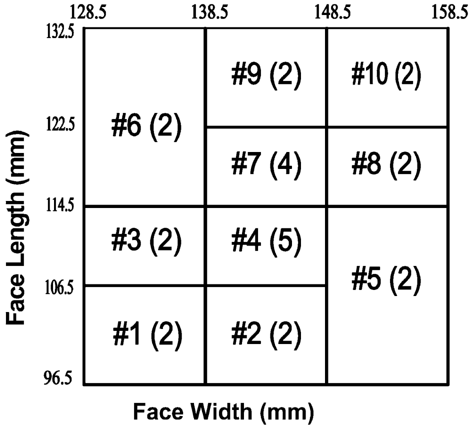

Fig 4. Chinese bivariate panel based on face length and face width is shown. The cells are numbered 1–10 and the numbers in parenthesis indicate the number of subjects to be sampled from each cell. When the subject's face length or face width fall on boundaries, the subject is classified into the higher number cells with larger face dimensions.

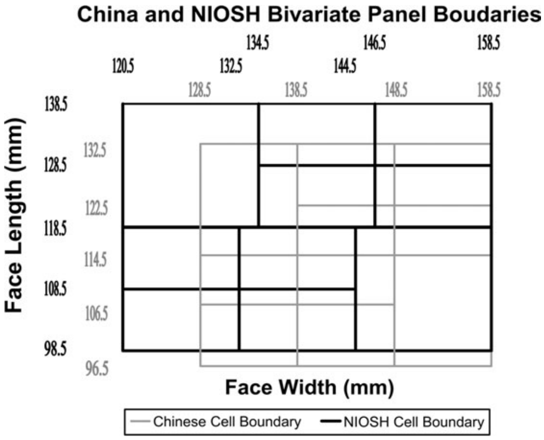

Fig 5. Boundary of Chinese bivariate panel in relation to the NIOSH bivariate panel.

Table 4. Summary statistics from PCA weighted to Chinese population

PC	Eigenvalue	Cumulative eigenvalue	Percentage total variance	Cumulative (%)
1	3.933	3.933	39.3	39.3
2	1.337	5.270	13.4	52.7
3	1.214	6.484	12.1	64.8
4	0.868	7.352	8.7	73.5
5	0.645	7.997	6.5	80.0
6	0.559	8.556	5.6	85.6
7	0.512	9.068	5.1	90.7
8	0.384	9.452	3.8	94.5
9	0.340	9.792	3.4	97.9
10	0.208	10.000	2.1	100.0

rationale for selecting the first two PCs using those criteria was previously reported (Zhuang *et al.*, 2007). In keeping with the simplicity of the NIOSH PCA panel, only the first two PCs were used to construct the Chinese PCA fit test panel even though the third PC was very close to the Kaiser criterion (i.e. only use PCs with eigenvalues >1). The PCA scores calculated from the two components will allow the panel to be based upon two-dimensional scatter plots and thus can be easily compared to the previous LANL panel and the new NIOSH bivariate panel (Table 5). The distribution of Chinese subjects into the Chinese PCA fit test panel is shown in Figure 6. The distribution of survey subjects within the Chinese bivariate panel is now uniform and each cell contains at least 10% of the population (Table 6). This panel covers 95.2% of the male and 97.6% of the female Chinese civilian work force.

The layout of the Chinese PCA panel cells is different from the bivariate panel (Figure 6). The limit of this panel is based on an ellipse in which >95% of the population is included. The inner ellipse includes about one-third of the population. The rationale for the rest of the PCA configuration is to

Table 5. Eigenvectors from PCA weighted to Chinese population

Face dimensions	PC1	PC2
Minimum frontal breadth	0.322260	−0.388836
Face width	0.422051	−0.140757
Bigonial breadth	0.328562	−0.227790
Face length	0.244826	0.568632
Interpupillary distance	0.370307	−0.159748
Head breadth	0.373045	−0.132683
Nose protrusion	0.237882	0.308739
Nose breadth	0.321181	0.079405
Nasal root breadth	0.159204	−0.173192
Subnasale–sellion length	0.297905	0.528574

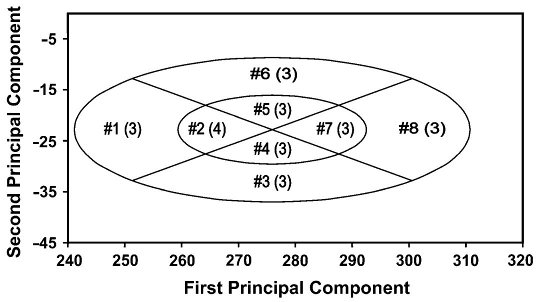

Fig 6. Chinese PCA panel based on two PCs is shown. The cells are numbered 1–8 and the numbers in parentheses indicate the number of subjects to be sampled from each cell. The fourth subject from cell 2 may be replaced with a fourth subject from cells 4, 5 or 7 if it is easier to get the fourth subject from these cells.

Table 6. Percentage of population and number of subjects for the Chinese panel based on two PCs

Cell	Male (%)	Female (%)	Total (%)	Male	Female	Total
1	1.7	22.6	12.2	0	3	3
2	5.3	23.7	14.6	1	3	4
3	7.1	14.9	11.0	1	2	3
4	7.9	17.7	12.8	1	2	3
5	15.8	8.6	12.2	2	1	3
6	16.5	6.6	11.5	2	1	3
7	17.5	3.5	10.4	2	1	3
8	23.3	0.5	11.8	3	0	3
Total	95.1	98.1	96.5	12	13	25

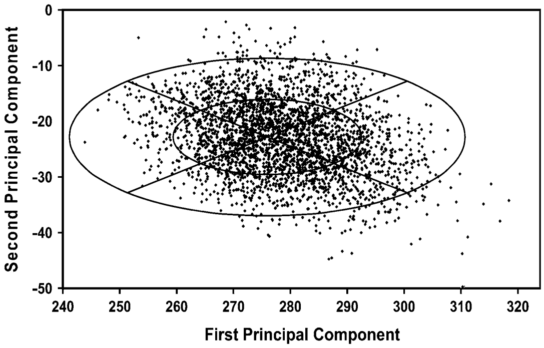

Fig 7. Scatter plot of PCs scores is shown along with the Chinese PCA panel.

have uniform distributions for each cell. Thus, two lines were used to divide the two ellipses into four quadrants resulting in eight cells. The population is then uniformly distributed among cells. Figure 7 shows the scatter plot of the distribution of the scores from the first two PCs for the Chinese subjects and the boundaries of the new PCA panel.

The eigenvectors from the PCA are provided in Table 5. The eigenvectors for each PC are used to multiply the original 10 face dimensions to obtain the scores for each PC. A rotation was performed using the variance maximizing method, but the coefficients are similar to the original coefficients. Thus, the original coefficients were used to develop the PCA panel.

The eigenvectors for PC1 are all positive. Thus, in general, subjects with larger faces (i.e. higher values for the 10 facial dimensions) will also tend to have larger PC1 scores. However, facial measurements that describe the width of the face (e.g. face width, interpupillary distance and head breadth) contribute the most to the first PC. Thus, the first PC captures the overall width of the face. Subjects with wider faces will fall into the right-most portion of the PCA plot shown in Figure 7, while those with thinner faces will fall into the left side of the plot. PC1 reflects larger and smaller face widths is not surprising given seven of the 10 variables are face widths. The magnitudes of the eigenvectors for the second PC are more diverse. The eigenvectors for PC2 are negative with the exception of face length, nose protrusion and subnasale–sellion length. Minimal frontal breadth had the largest negative eigenvector. Face width, interpupillary distance, head breadth, nose breadth and nasal root breadth were close to zero and have little impact on PC2. Thus, the second PC captures face shape, primarily key features related to face length and nose depth. As dimensions with negative eigenvectors increases, their PC2 score decreases. For the three dimensions with positive eigenvectors, it is the opposite. For subjects with large narrow noses and long face lengths, their PC2 scores are large. For subjects with large nose protrusions and short face lengths, their PC2 scores are small and thus will be found in the lower portion of the scores plot.

To use the PCA panel, the 10 face dimensions needed to be first measured as described previously (Zhuang *et al.*, 2007). The first and second PCs (PC1 and PC2) are then calculated as follows.

$$
\begin{aligned}
\mathrm{PC1} = {} & 0.322260(\text{minimum frontal breadth}) \\
& + 0.422051(\text{face width}) + 0.328562 \\
& (\text{bigonial breadth}) + 0.244826 \\
& (\text{menton} - \text{sellion length}) + 0.370307 \\
& (\text{interpupillary distance}) + 0.373045 \\
& (\text{head breadth}) + 0.237882 \\
& (\text{nose protrusion}) + 0.321181 \\
& (\text{nose breadth}) + 0.159204(\text{nasal root breadth}) \\
& + 0.297905(\text{subnasale} - \text{sellion length}).
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{PC2} = {} & -0.388836(\text{minimum frontal breadth}) \\
& - 0.140757(\text{face width}) - 0.227790 \\
& (\text{bigonial breadth}) + 0.568632 \\
& (\text{menton} - \text{sellion length}) - 0.159748 \\
& (\text{interpupillary distance}) - 0.132683 \\
& (\text{head breadth}) + 0.308739(\text{nose protrusion}) \\
& - 0.079405(\text{nose breadth}) - 0.173192 \\
& (\text{nasal root breadth}) + 0.528574 \\
& (\text{subnasale} - \text{sellion length}).
\end{aligned}
$$

Following the calculation of PC1 and PC2, the algorithm in Appendix 1 can be used to determine which cell the subject is in.

DISCUSSION

New Chinese respirator fit test panels have been developed using the traditional bivariate approach and a new approach based on PCA. The bivariate panel based on face length and face width is easy to use and is expected to cover >95% of the Chinese civilian workers. The panel size is 25 subjects for testing one-size fits all models. This sample size is the same as that suggested by Zhuang et al. (2007) in the development of the NIOSH bivariate panel and the LANL panel. It is a compromise between the need for a sufficient number of tests to develop good statistics and the requirement to test all devices submitted for approval in a reasonable length of time. Government regulatory bodies, researchers and standards development organizations using the panel can decrease or increase the panel size—depending upon their specific needs—using the percentages in Table 3. For respirator designs that come in multiple sizes, various combinations of cells and panel sizes can be used as part of a respirator certification process as noted previously (Zhuang *et al.*, 2007).

The boundary limits of the new panel are different from the LANL panel and the NIOSH bivariate panel. How well the NIOSH bivariate panel represents the current Chinese work force was investigated by comparing the percentage of subjects in the NIOSH cells versus the Chinese panel cells. The results are summarized in Table 7. However, it could be argued that the Chinese bivariate panel is actually a subset of the NIOSH bivariate panel. All boundaries fall within the NIOSH panel except for the lower limit of face length, which is shorter by 2.5 mm. The Kappa statistic was used to measure the degree of association between the NIOSH bivariate panel and the new Chinese bivariate panel (Rosner 2000). The Kappa statistic was 0.25 ($K > 0.75$ denotes excellent reproducibility; $0.4 \leq K \leq 0.75$ denotes good reproducibility; $0 \leq K < 0.4$ denotes marginal reproducibility). Statistically, this provides justification for the creation of new bivariate panels specific to the Chinese work force. The new Chinese bivariate panel should be useful for selecting subjects for testing and research on both half-facepiece respirators and full-facepiece respirators. Further studies will be needed to validate the panels; the experiments conducted recently by Zhuang *et al.* (2008) to support the selection of the facial dimensions for the NIOSH bivariate and PCA respirator fit test panels may be appropriate for these panels as well.

Recently, Yang and Shen (2008) conducted a facial anthropometric survey using 461 teachers and students from Zhongyuan University of Technology and Donghua University and used those results to develop a new bivariate panel specific to the Chinese population. They found mean face length and face width values of males to be 116.1 ± 7.4 and 146.2 ± 9.5 mm respectively. These values are smaller by ~1 mm compared to the measurements collected by Tongji Medical College (Du *et al.*, 2008). The mean face length and face width values for females were also smaller with values of 104.2 ± 5.8 and 137.3 ± 6.9 mm, respectively. Face length is almost 6 mm shorter and the mean face width is 2.5 mm narrower than the mean face length for females in the Tongji Medical College survey. Yang and Shen created a bivariate panel with face width values ranging from 119.5 to 167.5 mm and face length values ranging from 92.5 to 132.5 mm.

The new Chinese bivariate panel developed in this study has limits of 128.5–158.5 mm for face width and 96.5–132.5 mm for face length. When comparing these limits with the results of the CNIS 1998 study, it can be found that the new Chinese bivariate panel based on the data from the Tongji Medical College survey adequately represents the 1998 sample population. Ninety-five percent of the population is represented by the mean value ± 2 SDs. The lower limits (mean of female − 2 SD) of face width and face length for CNIS are 128.6 and 97.6 mm,

Table 7. Percentage of population for each cell based on NIOSH panel by Chinese panel

China bivariate cell	NIOSH bivariate cell											
	1	2	3	4	5	6	7	8	9	10	N/A[a]	Total
1	16.0	75.5									8.5	100.0
2		63.6			33.8						2.6	100.0
3	8.3	31.7	7.8	52.2								100.0
4		20.4		40.9	38.7							100.0
5					100.0							100.0
6			8.1	51.4		7.2	29.7		3.6			100.0
7				38.3	31.9		22.8	7.0				100.0
8					65.2			34.8				100.0
9							66.0	22.8	8.2	3.0		100.0
10								87.5		12.5		100.0
N/A[a]	4.9		4.9			2.9			7.9	20.6	58.8	100.0

Blank cells represent 0.0%.
[a]N/A represents outliers.

respectively, while the upper limits (mean of male + 2 SD) for face width and face length are 150.8 and 132.2 mm, respectively (CNIS, 1998). All limits of the CNIS 1998 study are contained within the bivariate panel developed by this study.

The Chinese PCA panel is more complicated than the Chinese bivariate panel due to the acquisition of eight additional dimensions which can increase the time it takes for a human test subject to complete a respirator fit test. However, additional measurements may provide a more representative selection of face sizes for the test panel, which may lead to better fitting respirators for the population as a whole. Similar to the new bivariate panel, a single PCA panel may also be used for testing both half-facepiece and full-facepiece respirators.

Similar to the Chinese bivariate panel, the recommended panel size for the Chinese PCA panel is 25 subjects for testing one-size fits all models. Other options for choosing specific cells and/or increasing the size of the panel to account for respirator designs with multiple sizes have been discussed previously (Zhuang *et al.*, 2007) and can be applied for this panel as well.

Similar to the findings of Zhuang *et al.* in the development of NIOSH PCA panel, the nine dimensions that were excluded in the PCA model have good correlations ($P < 0.01$) with the 10 dimensions selected and can be well predicted by the 10 dimensions (Table 8). For example, maximum frontal breadth was excluded, but the R^2 was 0.79 for the multiple regression model between maximum frontal breadth and the 10 dimensions. If it is found to be more relevant to the fit of full-facepiece respirators in the future, its variation has already been well described by the 10 dimensions and there is no need to revise the PCA panel. Thus, the PCA model provides a strong framework that can take into account future developments more easily than the simpler bivariate panel.

Table 8. Summary of R^2 values for multiple regression analyses between each of the face dimensions excluded from the Chinese PCA model and the 10 face dimensions included in the Chinese PCA model

Face dimensions	R^2	P
Max frontal breadth	0.79	<0.01
Bitragion frontal arc	0.68	<0.01
Neck circumference	0.67	<0.01
Bitragion chin arc	0.66	<0.01
Bitragion subnasale arc	0.64	<0.01
Head circumference	0.62	<0.01
Bitragion coronal arc	0.55	<0.01
Head length	0.41	<0.01
Lip length	0.26	<0.01

The first PCs are very similar between the Chinese and US populations and both represent the overall size of the human head. However, the second PCs have opposite signs as shown in Figs 2 and 7 indicating that facial shape between the two populations is quite different. The Chinese PCA panel described here created using data from the Chinese work force may be useful for certain applications.

CONCLUSIONS

Overall, 95% of the workers in the 2006 Chinese survey fall within the NIOSH bivariate and PCA panels, suggesting that if these panels are incorporated into international standards for respiratory protective devices, they will be appropriate for the Chinese population as well. However, distribution across the panel was not uniform; only 6.3% fell into cells 1, 3, 6, 9 and 10 of the bivariate panel and 7.2% are found within cells 1, 5 and 6 of the PCA panel. Therefore, new test panels with subject dimensions and distributions specific to Chinese workers may be beneficial for some applications. With the increasing prominence of China in manufacturing, and ever increasing construction in China, along with its large population (1.3 billion), the development of representative respirator fit test panels is especially important to protect the large number of Chinese workers.

Two respirator fit test panels were developed with the same techniques used to create the NIOSH panels. The bivariate approach used face length and face width measurements, weighted to match age and gender distributions of the Chinese population from the 2005 census. The PCA panel was developed using the first two PCs obtained from a set of 10 facial dimensions (age and gender adjusted). Respirators designed to fit these panels are likely to accommodate >95% of Chinese workers.

FUNDING

Program for New Century Excellent Talents in University in China (NCET-05-0646 to W.Chen.).

APPENDIX 1

Algorithm for classifying test subjects into the PCA panel cells

$x = \text{PC1} - 275.9362583$
$y = \text{PC2} + 22.8173892$
$\text{slope} = 6.6138444/11.0533488 = 0.5983566$
$a = 2.54 \times 11.0533488$
$b = 2.54 \times 6.6138444$
$c = 1.175 \times 11.0533488$

$d = 1.175 \times 6.6138444$

$$r1 = \sqrt{(x^2)/(a^2) + (y^2)/(b^2)}$$

$$r2 = \sqrt{(x^2)/(c^2) + (y^2)/(d^2)}$$

where

x and *y* are new co-ordinates for translating the origin of PC1 and PC2 from their mean values (275.9362583 for PC1 and −22.8173892 for PC2) to zero

slope is the slope value for the two lines dividing the ellipse into eight cells

a is the constant for the length of the semimajor axis for the outer ellipse

b is the constant for the length of the semiminor axis for the outer ellipse

c is the constant for the length of the semimajor axis for the inner ellipse

d is the constant for the length of the semiminor axis for the inner ellipse

$r1$ and $r2$ are calculated values to determine where a particular data point or a subject is, e.g. the data point is outside the outer ellipse when $r1 > 1$ or on the outer ellipse when $r1 = 1$ or inside the outer ellipse when $r1 < 1$.

Use the *x*, *y* and $r1$ values and the algorithm below to determine if the subject is in cells 1, 3, 6 and 8:

if $x \geq 0$ and $y \geq 0$ and $r1 \leq 1$ and abs (y)/abs$(x) \leq$ slope, then cell = 8

if $x \geq 0$ and $y < 0$ and $r1 \leq 1$ and abs (y)/abs$(x) <$ slope, then cell = 8

if $x \geq 0$ and $y < 0$ and $r1 \leq 1$ and abs (y)/abs$(x) \geq$ slope, then cell = 3

if $x < 0$ and $y < 0$ and $r1 \leq 1$ and abs (y)/abs$(x) >$ slope, then cell = 3

if $x < 0$ and $y < 0$ and $r1 \leq 1$ and abs (y)/abs$(x) \leq$ slope, then cell = 1

if $x < 0$ and $y \geq 0$ and $r1 \leq 1$ and abs (y)/abs$(x) <$ slope, then cell = 1

if $x < 0$ and $y \geq 0$ and $r1 \leq 1$ and abs (y)/abs$(x) \geq$ slope, then cell = 6

if $x \geq 0$ and $y \geq 0$ and $r1 \leq 1$ and abs (y)/abs$(x) >$ slope, then cell = 6

If the $r2$ value ≤ 1, use the following algorithm to adjust the cell number

if cell = 8 and $r2 \leq 1$, then cell = 7

if cell = 3 and $r2 \leq 1$, then cell = 4

if cell = 1 and $r2 \leq 1$, then cell = 2

if cell = 6 and $r2 \leq 1$, then cell = 5

Acknowledgements—Disclaimer—The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the NIOSH.

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