Facial Anthropometric Differences among Gender, Ethnicity, and Age Groups

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Objectives: The impact of race/ethnicity upon facial anthropometric data in the US workforce, on the development of personal protective equipment, has not been investigated to any significant degree. The proliferation of minority populations in the US workforce has increased the need to investigate differences in facial dimensions among these workers. The objective of this study was to determine the face shape and size differences among race and age groups from the National Institute for Occupational Safety and Health survey of 3997 US civilian workers.

Methods: Survey participants were divided into two gender groups, four racial/ethnic groups, and three age groups. Measurements of height, weight, neck circumference, and 18 facial dimensions were collected using traditional anthropometric techniques. A multivariate analysis of the data was performed using Principal Component Analysis. An exploratory analysis to determine the effect of different demographic factors had on anthropometric features was assessed via a linear model. The 21 anthropometric measurements, body mass index, and the first and second principal component scores were dependent variables, while gender, ethnicity, age, occupation, weight, and height served as independent variables.

Results: Gender significantly contributes to size for 19 of 24 dependent variables. African-Americans have statistically shorter, wider, and shallower noses than Caucasians. Hispanic workers have 14 facial features that are significantly larger than Caucasians, while their nose protrusion, height, and head length are significantly shorter. The other ethnic group was composed primarily of Asian subjects and has statistically different dimensions from Caucasians for 16 anthropometric values. Nineteen anthropometric values for subjects at least 45 years of age are statistically different from those measured for subjects between 18 and 29 years of age. Workers employed in manufacturing, fire fighting, healthcare, law enforcement, and other occupational groups have facial features that differ significantly than those in construction.

Conclusions: Statistically significant differences in facial anthropometric dimensions ($P < 0.05$) were noted between males and females, all racial/ethnic groups, and the subjects who were at least 45 years old when compared to workers between 18 and 29 years of age. These findings could be important to the design and manufacture of respirators, as well as employers responsible for supplying respiratory protective equipment to their employees.

Keywords: anthropometrics; facial dimensions; respirator design; respiratory protection

INTRODUCTION

A properly fitted respirator is essential to the safety and health of workers who are employed in occupations that expose them to potential inhalation

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hazards (Coffey *et al.*, 2006) and to emergency response personnel who may be called upon to respond in hazardous environments (Zhuang *et al.*, 2005). Extensive use of anthropometric measurements and fit panels in establishing design and sizing requirements for respirators has been utilized or available in the USA since 1973 (Zhuang *et al.*, 2004). Criteria for respirator sizing have been based on military data collected from men and women of the United States Air Force (USAF) Anthropometry Survey taken in 1967–1968 (Clauser *et al.*, 1972). The Los Alamos National Laboratory-standardized adult head shape panels were developed based on the USAF craniofacial anthropometry data, and these panels are currently used in the National Institute for Occupational Safety and Health (NIOSH) respirator certification process (Hack *et al.*, 1974; Hack and McConville, 1978).

The panel for full-facepiece respirators is defined by face length (menton–sellion length) and face width (bizygomatic breadth). The panel for half-facepiece respirators is defined by face length and lip length (bicheilion breadth) (Zhuang *et al.*, 2005). The US population demographics have changed significantly over the past 30 years (Zhuang and Bradtmiller, 2005). In addition to increased body size and facial measurements, the current US workforce consists of a higher proportion of minorities when compared to the USAF data (2000 US census). In response to these demographic dynamics, NIOSH created a craniofacial anthropometric database detailing the face-size distributions of the current US workforce (Zhuang and Bradtmiller, 2005).

Discrepancies noted in the USAF data populace and current US workforce populations make it evident that workers in occupations requiring respirator use may not be adequately protected by relying on sizing data that is now four decades old. The 1967–1968 Air Force survey data are not reflective of the anthropometric distribution of the current US workers (Zhuang *et al.*, 2004). Brazile *et al.* (1998) concluded that respirator fit was not associated with facial dimensions based on race/ethnicity or gender and seemed to be associated with individual facial characteristics. Nonetheless, Zhuang *et al.* (2004) noted statistically significant differences for face length, face width, and lip length among ethnic/racial groups of US workers. The statistical analysis showed African-Americans to have significantly different face length and lip length from Caucasian, Hispanics, and the other race/ethnic groups. In addition, face width of African-Americans, Hispanics, and others were all significantly different from the Caucasian race group (Zhuang *et al.*, 2004), thereby providing scientific evidence for the need of civilian

data. This study was undertaken to ascertain any potential impact of race/ethnicity upon face shape and size differences in the US civilian workforce population. Any reference to shape in this study corresponds to the definition inherent to geometric morphometric analysis of landmark data and is defined as ' . . . the geometrical properties of an object invariant to location, scale, and orientation' (Slice, 2005). The purpose of this study was to determine the face shape and size differences among race and age groups and to identify dimensions with significant differences that may be essential for the design of properly fitted respirators.

METHODS

Subjects

In 2003, NIOSH conducted a nationwide anthropometric survey. Subjects were obtained from several occupational backgrounds that utilize respirators on a regular basis: construction, manufacturing, fire fighting, healthcare, law enforcement, and other occupational groups. As shown in Table 1, the 3997 study subjects were divided into three age strata (18–29, 30–44, and ≥45), two gender strata, and four racial/ethnic group strata [Caucasian, African-Americans, Hispanic, and other (mainly Asian)] (Zhuang *et al.*, 2005). Hispanic was chosen for the demographic data questionnaire to match the wording used by the US Census of 2000. Employing traditional anthropometric techniques, measurements of height, weight, neck circumference, and 18 facial dimensions were collected (Table 2). A description of the skeletal and skin points located on the face and head has been provided in Table 3. Once landmarks were designated (Fig. 1), the linear distance between the landmarks was measured. In addition to the collection of facial dimensions, body mass index (BMI) was also determined. BMI is defined as an individual's weight in kilograms divided by their height in meters squared. The results of these body measurements and BMI values were used to investigate differences between gender, racial/ethnic groups, age groups, and occupational groups.

Principal component analysis

A multivariate analysis of the data was performed using Principal Component Analysis (PCA) in the SAS® program (SAS 2008). The analysis used a subset of 10 facial dimensions (bigonial breadth, face width, minimal frontal breadth, face length, nose length, nasal root breadth, nose breadth, interpupillary

Table 1. Distribution of subjects by gender, race, and age group

Race	Male			Total	Female			Total
	Age group (years)				Age group (years)			
	18–29	30–44	45–66		18–29	30–44	45–66	
White	271	611	485	1367	151	194	174	519
African-Americans	101	255	278	634	51	213	325	589
Hispanic	155	182	75	412	53	36	37	126
Other	24	47	59	130	52	65	103	220
Total	551	1095	897	2543	307	508	639	1454

Table 2. The definition for each anthropometric measurement collected during this study

Stature	Vertical distance as measured with an anthropometer between the standing surface and the top of the head
Weight (kg)	Body weight of the subject taken to the nearest half kilogram
BMI	Weight/(height/100)^2, weight in kilograms and height in centimeters
Bigonial breadth	Straight-line distance measured with a spreading caliper between the right and left gonion landmarks on the corners of the jaw
Bitragion chin arc	Distance as measured with a tape between the right and left tragion landmarks across the anterior point of the chin
Bitragion coronal arc	Distance as measured with a tape between the right and left tragion landmarks across the top of the head in the coronal plane
Bitragion frontal arc	Distance as measured with a tape between the right and left tragion landmarks across the forehead just above the supraorbital ridges
Bitraion subnasale arc	Distance as measured with a tape between the right and left tragion landmarks across the subnasale landmark
Face width	Maximum horizontal breadth of the face as measured with a spreading caliper between the zygomatic arches
Head breadth	Maximum horizontal breadth of the head as measured with a spreading caliper above the level of the ears
Head length	Maximum length as measured with a spreading caliper in the midsagittal place
Interpupillary distance	Distance as measured with a pupillometer at the center of the right and the center of the left pupil
Bicheilion breadth (lip length)	Straight-line distance as measured with a sliding caliper between the right and left cheilion landmarks at the corner of closed mouth
Maximum frontal breadth	Straight-line distance as measured with a spreading caliper between the right and left zygofrontale landmarks at upper margin of each bony eye socket
Face length	Distance as measured with a sliding caliper in the midsagittal plane between the menton landmark and the sellion landmark
Minimum frontal breadth	Straight-line distance as measured with a spreading caliper between the right and left Frontotemporale landmarks
Nasal root breadth	Horizontal breadth of nose as measured with a sliding caliper at the sellion landmark and a depth equal to one-half the distance from the bridge of the nose to the eyes
Nose breadth	Straight-line distance as measured with a sliding caliper between the right and left alare landmarks
Nose protrusion	Straight-line distance as measured with a sliding caliper between the Pronasale landmark and the Subnasale landmark
Nose length	Straight-line distance as measured with a sliding caliper between the subnasale landmark and the sellion landmark
Head circumference	Circumference of head as measured with a tape just above the supraorbital ridges
Neck circumference	Circumference as measured with a tape at the neck

breadth, nose protrusion, and head breadth), all of which were relevant to respirator fit and were shown to have a significant correlation with predicting the other eight dimensions. The details of this analysis including the equations used to calculate the first and second principal components have been previously published (Zhuang *et al.*, 2007). By using a linear combination of these variables, PCA defines a new coordinate system to describe trends in the data that contribute most to variation in the linear measurements. Using the PCA method, it allows for analysis of any trend within the 10 dimensions to better

Table 3. Landmark definitions and a description of their locations

| Landmark	Numbers on Fig. 1	Description
Alare	24 and 25	Lateral point on the flare or wing of the nose
Cheilion	12 and 13	Lateral point of the juncture of the fleshy tissue of the lips with the facial skin at the corner of the mouth
Chin	26	Most protruding point on the bottom edge of the chin along jawline
Ectocanthus		Outside corner of the right eye formed by the meeting of the upper and lower eyelids
Frontotemporale	5 and 16	Point of deepest indentation of the temporal crest of the frontal bone above the browridges
Glabella	7	The anterior point on the frontal bone midway between the bony browridges
Gonion	3 and 18	Most lateral, most inferior, and most posterior point on the angle of the mandible
Infraorbitale		Lowest point on the anterior border of the bony eye socket
Menton	11	Inferior point of the mandible in the midsagittal plane
Nasal root point	22 and 23	Point on the right side of the nasal root at a depth equal to one-half distance from the bridge of the nose to eyes
Pronasale	9	Point of the anterior projection on the tip of nose
Sellion	8	Point of the deepest depression of the nasal bones at the top of the nose
Subnasale	10	Point of intersection of the philtrum with the inferior surface of the nose
Top of head		Highest point on the head when the head is in the Frankfort plane
Tragion	1 and 17	Superior point on the juncture of the tragus of the ear with the head
Zygion	2 and 19	Most lateral point on the zygomatic arch
Zygofrontale	5 and 16	Lateral point of the frontal bone on its zygomatic process
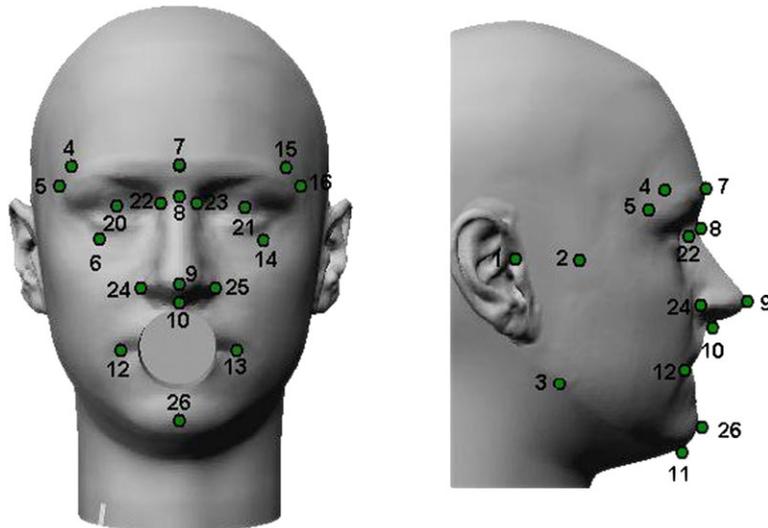
Fig 1. The landmark location for the facial measurements as indicated by Table 3.

visualize the relative differences of those facial dimensions for each gender, racial/ethnic, age, and occupational group.

Linear regression

An exploratory analysis to determine the effect of different demographic factors on anthropometric features was assessed via a linear model. The 21 anthropometric measurements, BMI values, and the first and second principal component values served as the outcomes (e.g. dependent variables), while gender, ethnicity, age, occupation, weight, and height served as covariates (e.g. independent variables). Gender, ethnicity, occupation, and age were

entered as factors with two, four, six, and three categories, respectively. Caucasian males, between 18 and 29 years of age employed as construction workers, were treated as the baseline, and separate effects (versus the baseline) were estimated for females, the remaining racial/ethnic groups, and the other age and occupational groups. Both weight and height were left continuous, with 10 kg and 100 mm, respectively, treated as a one-unit change.

Regression was chosen due to its ability to properly assess the effects of both continuous and categorical variables, as well as its ability to deal with the unbalanced sample sizes present for certain variables in the dataset. The linear model finds the best linear combination of those factors (i.e. set of coefficients for each independent variable) that produces a predicted outcome (anthropometric measurement) as close as possible to the observed outcome across all subjects. All models were fit using SAS statistical software. The resulting coefficients for each demographic feature can be interpreted as the average differences in the given outcome variable (anthropometric feature) for subjects in the given category versus the baseline (for age, race/ethnicity, and gender) or the average differences associated with a one-unit change in the given variable, while holding all other variables constant. Using the linear model is preferable (for this analysis) to stratification since one can easily assess the effect of a given factor, while controlling for all other factors. Since there are no interactions in the model, the effect of differences in a given demographic feature is assumed to be independent of the level of all other factors.

RESULTS

PCA

The first principal component (PC1) represents the overall size of the face, while the second principal component (PC2) is indicative of the overall width of the face. Each principal component was calculated using equations that have been previously published and includes the value of 10 critical dimensions relevant to half-mask respirator fit (minimal frontal breadth, face width, face length, bigonial breadth, nose length, nose protrusion, nose breadth, nasal root breadth, interpupillary breadth, and head breadth) (Zhuang *et al.*, 2007). In the course of this study, significant differences in shape and size were found between males and females, among all four racial/ethnic groups, between occupational groups, and among all three age groups.

Individuals with small heads aggregate into cell 1, medium heads into cells 2, 4, 5, and 7, large heads into cell 8, long/narrow heads into cell 6, and short/wide heads into cell 3 (Fig. 2). Fig. 3 shows the distribution of each group in relation to the baseline. Since the PCA panels permit comparison of overall face size and shape, it visually illustrates that gender makes the greatest contribution to differences in facial characteristics. Even though females and males fall within the medium size category, females are located closer to the small face size category, while males are shifted toward the large face size category. The second factor that contributes to differences in facial characteristics is race/ethnicity. African-Americans and the other ethnic group seem to have larger and shorter faces than Caucasians, while Hispanics have larger faces than Caucasians. The differences resulting from age are not significant until employees reach 45 years of age; older workers tend to have larger and longer narrower faces.

Linear regression analysis

Table 4a and b displays the results of the linear regression model. Consider the neck circumference in Table 4a. The baseline average of 397.6 indicates that a Caucasian male <30 years of age and of average weight (78.7 kg) and average height (1762.2 mm) would have an average (or predicted) neck circumference of 398 mm. Leaving all other
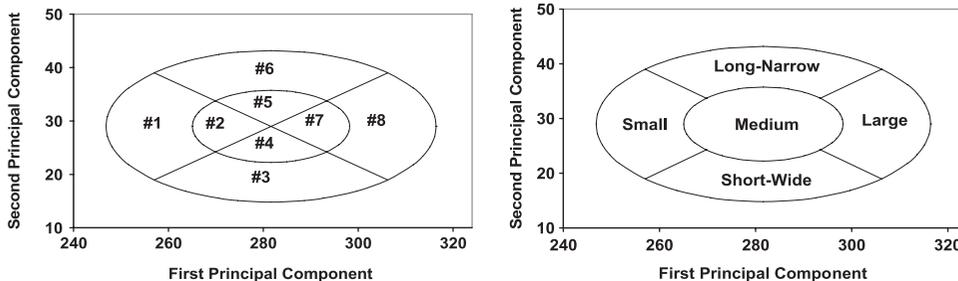

Fig 2. The PCA respirator fit test panel (left) and the five face size categories (right).
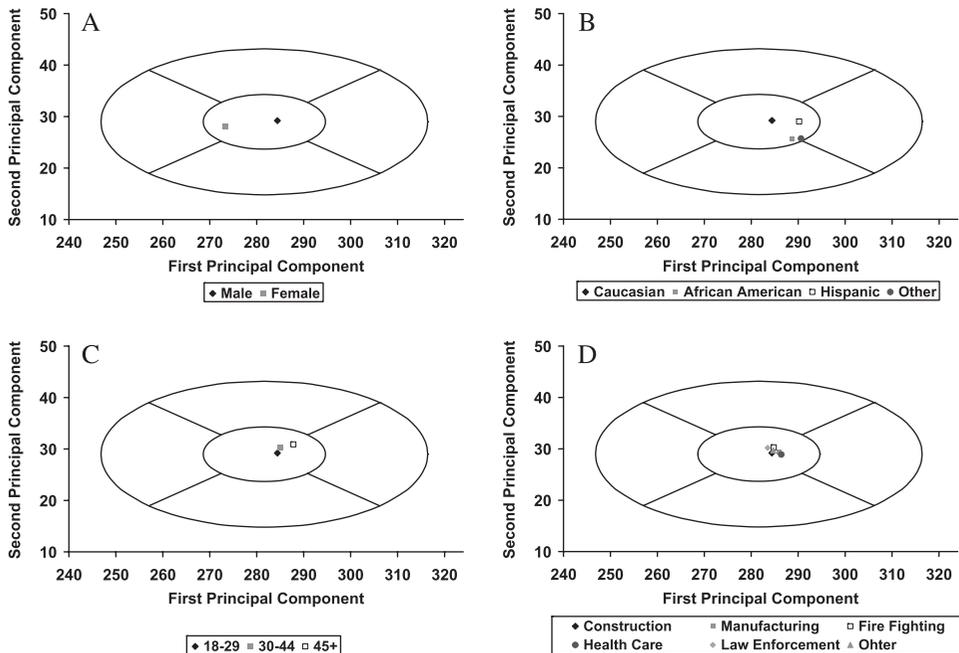
Fig 3. The face size category distribution of gender (A), ethnicity (B), age group (C), and occupation (D).

factors constant, a subject would have a larger neck circumference by 5.6 mm on average for the 30- to 44-year-old category and by 9.0 mm for the 45 year and older group.

Gender. Gender significantly contributes to size for 19 of 24 dependent variables. Women have smaller anthropometric measurements for every dimension. Only nasal root breadth, weight, and BMI resulted in values that were not significantly different from males. The overall size of female faces is smaller than males with an average change (AC) of −11.1 for PC1. They also have shorter narrower faces indicated by an AC of −1.2 for PC2.

Race/ethnicity. In this study, African-Americans have statistically shorter, wider, and shallower noses than Caucasians. They are shorter but weigh more resulting in higher BMI than Caucasians. All remaining features are significantly larger for African-Americans than Caucasians except for bigonial breadth, bitragion coronal arc, head breadth, and neck circumference where there was no statistical difference between these dimensions. Overall, African-Americans have larger faces than Caucasians (AC = 4.3) for PC1, and the width of their face and nose is wider as indicated by a decrease in PC2 (AC = −3.6). Hispanic workers have 14 facial features that are significantly larger than Caucasians, while their nose protrusion, height, and head length

are significantly shorter. There was no difference between Hispanic and Caucasian head circumference, minimal frontal breadth, nasal root breadth, and neck circumference. Hispanic workers have faces that are larger than Caucasians as indicated by PC1 (AC = 4.3). The other ethnic group was composed primarily of Asian subjects and has statistically different dimensions from Caucasians for 16 anthropometric values. Similar to African-Americans, the other ethnic group had larger faces with increased widths of the face and nose as indicated by PC1 (AC = 6.2) and PC2 (AC = −3.5).

Age. Nineteen anthropometric values for subjects at least 45 years of age are statistically different from those measured for subjects between 18 and 29 years of age. Bitragion frontal arc, head circumference, and maximal frontal breadth are statistically equivalent for these two groups. Differences in facial features between the youngest age group and those between the ages of 30 and 44 were not as prevalent, with seven dimensions statistically equivalent to one another. The most notable differences between these groups were found for neck circumference, weight, and height. When using the PCA value to evaluate face size and shape, there is an increase in PC1 and PC2 indicating that older workers have significantly larger faces, with longer narrower features.

Table 4. Regression coefficients for anthropometric measurements adjusted for gender, race, age, weight, and height

Facial dimension	Baseline average (SE)	Gender (versus male) Female AC (SE)	Race (versus Caucasian)			Age (versus 18–29)		Occupation (versus construction)					Weight AC per 10 kg (SE)	Height AC per 100 mm (SE)
			AA AC (SE)	Hispanic AC (SE)	Others AC (SE)	30–44 AC (SE)	$\geq$45 AC (SE)	MF AC (SE)	FF AC (SE)	HC AC (SE)	LE AC (SE)	Other AC (SE)		
a														
Bitragion chin arc	322.7 (0.6)	−16.1 (0.6)*	9.4 (0.5)*	8.3 (0.6)*	8.5 (0.7)*	1.2 (0.5)**	3.4 (0.5)*	1.2 (0.7)	1.1 (0.6)	1.1 (0.7)	−0.3 (1.1)	−0.2 (0.8)	4.6 (0.1)*	2.8 (0.3)*
Bitragion coronal arc	348.0 (0.7)	−3.4 (0.7)*	−0.2 (0.6)	5.1 (0.7)*	6.2 (0.9)*	−1.7 (0.6)*	−1.5 (0.6)**	−1.9 (0.9)**	0.2 (0.8)	2.2 (0.8)*	−3.6 (1.3)*	1.0 (0.9)	2.1 (0.1)*	4.0 (0.4)*
Bitragion frontal arc	302.0 (0.6)	−9.3 (0.6)*	1.7 (0.5)*	2.2 (0.6)*	5.2 (0.7)*	−0.4 (0.5)	1.0 (0.5)	−3.3 (0.7)*	−0.7 0.6	−2.0 (0.7)*	−3.4 (1.1)*	1.0 (0.7)	2.7 (0.1)*	2.1 (0.3)*
Bitragion subnasale arc	289.8 (0.6)	−9.6 (0.6)*	9.1 (0.4)*	7.4 (0.6)*	9.2 (0.7)*	0.1 (0.5)	1.2 (0.5)**	−1.0 (0.7)	−0.3 (0.6)	0.4 (0.6)	−2.9 (1.0)*	0.0 (0.7)	3.8 (0.1)*	1.3 (0.3)*
Head circumference	567.9 (0.9)	−5.4 (0.8)*	6.8 (0.6)*	0.2 (0.8)	3.1 (1.0)*	−1.7 (0.7)**	−1.2 (0.7)	5.3 (1.0)*	5.1 (0.9)*	1.7 (0.9)	4.7 (1.5)*	0.8 (1.0)	3.8 (0.2)*	5.3 (0.4)*
Head length	195.0 (0.4)	−4.6 (0.3)*	1.5 (0.3)*	−2.3 (0.3)*	−3.1 (0.4)*	−0.8 (0.3)*	−0.8 (0.3)*	1.5 (0.4)*	2.8 (0.4)*	0.7 (0.4)	2.8 (0.6)*	1.0 (0.4)**	0.9 (0.1)*	2.7 (0.2)*
Lip length	48.6 (0.2)	−2.1 (0.2)*	3.7 (0.2)*	1.5 (0.2)*	0.1 (0.2)	1.3 (0.2)*	2.4 (0.2)*	−0.4 (0.2)	0.4 (0.2)	0.1 (0.2)	0.0 (0.4)	0.1 (0.2)	0.3 (0.0)*	0.4 (0.1)*
Maximal frontal breadth	110.6 (0.3)	−1.8 (0.3)*	2.1 (0.2)*	1.8 (0.3)*	1.4 (0.3)*	−0.2 (0.2)	0.3 (0.2)	0.2 (0.3)	0.3 (0.3)	1.1 (0.3)*	−0.1 (0.5)	0.3 (0.3)	1.0 (0.0)*	0.8 (0.1)*
Neck circumference	397.6 (2.9)	−50.1 (1.3)*	0.4 (1.1)	2.2 (1.6)	2.5 (1.6)	5.6 (1.2)*	9.0 (1.2)*	−1.9 (3.0)	−1.1 (2.8)	−3.6 (2.8)	−4.7 (3.6)	−2.2 (3.4)	14.0 (0.2)*	−5.7 (0.7)*
Weight	78.7 (0.9)	0.7 (0.9)	5.8 (0.7)*	5.7 (0.9)*	−7.7 (1.0)*	5.9 (0.7)*	8.3 (0.8)*	0.5 (1.1)	0.1 (0.9)	−0.2 (1.0)	−0.9 (1.6)	−1.8 (1.1)		10.4 (0.4)*
Height	1762.2 (3.1)	−105.0 (2.6)*	−5.0 (2.4)**	−54.4 (3.1)*	−31.5 (3.7)*	−7.4 (2.6)*	−18.8 (2.8)*	−2.3 (3.8)	17.3 (3.3)*	−6.9 (3.6)	17.8 (5.8)*	4.6 (3.9)	13.6 (0.5)*	
BMI	27.0 (0.3)	0.0 (0.2)	2.0 (0.2)*	1.9 (0.3)*	−3.2 (0.4)*	2.1 (0.3)*	2.9 (0.3)*	0.2 (0.4)	0.0 (0.3)	0.0 (0.3)	−0.3 (0.6)	−0.7 (0.4)		
b														
Bigonial breadth	119.2 (0.4)	−7.6 (0.4)*	−0.4 (0.3)	3.6 (0.4)*	4.9 (0.5)*	0.2 (0.4)	1.0 (0.4)*	1.6 (0.5)*	−2.2 (0.4)*	0.2 (0.5)	−1.4 (0.8)	−0.9 (0.5)	3.5 (0.1)*	−1.9 (0.2)*
Face width	141.5 (0.3)	−6.0 (0.3)*	0.8 (0.2)*	3.6 (0.3)*	5.0 (0.3)*	−0.1 (0.2)	0.9 (0.3)*	0.5 (0.3)	−0.3 (0.3)	1.0 (0.3)*	−1.2 (0.5)**	0.0 (0.4)	2.0 (0.1)*	0.1 (0.1)

Table 4. *Continued*

Head breadth	151.2 (0.3)	−4.7 (0.3)*	−0.4 (0.2)	1.5 (0.3)*	3.5 (0.3)*	−0.4 (0.2)	0.5 (0.3)**	0.9 (0.3)**	1.2 (0.3)*	1.4 (0.3)*	1.0 (0.5)	0.4 (0.4)	1.0 (0.1)*	0.5 (0.1)*
Inter pupillary distance	62.9 (0.2)	−1.3 (0.2)*	3.4 (0.1)*	1.3 (0.2)*	1.5 (0.2)*	0.7 (0.1)*	1.4 (0.2)*	−0.3 (0.2)	−0.5 (0.2)*	−0.1 (0.2)	−0.5 (0.3)	−0.3 (0.2)	0.4 (0.0)*	0.6 (0.1)*
Face length	118.2 (0.3)	−5.3 (0.3)*	2.7 (0.3)*	2.8 (0.3)*	−0.2 (0.4)	1.0 (0.3)*	2.1 (0.3)*	1.0 (0.4)*	2.0 (0.3)*	1.5 (0.4)*	0.3 (0.6)	1.0 (0.4)**	0.5 (0.1)*	2.6 (0.2)*
Minimal frontal breadth	104.0 (0.3)	−1.1 (0.3)*	0.5 (0.2)**	0.2 (0.3)	−0.5 (0.3)	−0.2 (0.2)	0.6 (0.2)*	0.2 (0.3)	0.9 (0.3)*	1.5 (0.3)*	0.4 (0.5)	0.7 (0.3)**	1.0 (0.1)*	0.5 (0.1)*
Nasal root breadth	16.4 (0.1)	−0.2 (0.1)	0.8 (0.1)*	0.2 (0.1)	0.2 (0.1)	−0.3 (0.1)*	−0.4 (0.1)*	0.5 (0.1)*	0.4 (0.1)*	0.6 (0.1)*	−0.5 (0.2)**	0.2 (0.1)	0.2 (0.0)*	0.0 (0.1)
Nose breadth	34.3 (0.2)	−3.0 (0.2)*	7.6 (0.1)*	2.7 (0.2)*	3.5 (0.2)*	0.5 (0.1)*	2.0 (0.1)*	−0.3 (0.2)	−0.2 (0.2)	0.1 (0.2)	−0.8 (0.3)*	0.0 (0.2)	0.4 (0.0)*	0.0 (0.1)
Nose protrusion	20.7 (0.1)	−0.3 (0.1)**	−2.3 (0.1)*	−0.7 (0.1)*	−2.1 (0.2)*	0.3 (0.1)**	0.5 (0.1)*	0.5 (0.2)*	0.2 (0.1)	0.2 (0.1)	0.8 (.2)*	0.4 (0.2)**	0.1 (0.0)*	0.7 (0.1)*
Nose length	50.5 (0.2)	−1.9 (0.2)*	−1.2 (0.2)*	0.9 (0.2)*	−1.2 (0.2)*	1.0 (0.2)*	2.3 (0.2)*	−0.5 (0.2)**	0.2 (0.2)	−0.9 (0.2)*	−0.2 (0.4)	0.0 (0.2)	−0.1 (0.0)*	1.2 (0.1)*
PCA1	284.4 (0.5)	−11.1 (0.4)*	4.3 (0.3)*	5.8 (0.5)*	6.2 (0.5)*	0.7 (0.4)**	3.4 (0.4)*	1.5 (0.5)*	0.4 (0.5)	2.0 (0.5)*	−0.9 (0.8)	0.3 (0.6)	3.4 (0.8)*	1.1 (0.2)*
PCA2	29.2 (0.3)	−1.2 (0.3)*	−3.6 (0.2)*	−0.2 (0.3)	−3.5 (0.3)*	1.0 (0.2)*	1.7 (0.2)*	0.1 (0.3)	1.1 (0.3)*	−0.3 (0.3)	1.0 (0.5)**	0.5 (0.3)	−0.6 (0.0)*	2.0 (0.1)*

AC is the average change from baseline to a group value, and SE represents the standard error for a group value; a 95% confidence interval can be calculated as AC ± 1.96 × SE; ethnic groups are designated as follows: African-Americans (AA) and Hispanic (HISP) refers to Hispanic workers; occupation is designated as follows: manufacturing (MF), firefighting (FF), healthcare (HC), and law enforcement (LE); units are in millimeter except for BMI, weight, PC1, and PC2.
$*P < 0.01$; $**P < 0.05$.

Table 5. Distribution of test subjects based on occupation and gender

Occupation	Male	Female	Total
Construction	594	47	641
Manufacturing	429	60	489
Fire Fighting	774	74	848
Healthcare	381	1098	1479
Law enforcement	121	7	128
Other	246	166	412
Total	2545	1452	3997

Occupation. The sample distribution of occupations by gender is shown in Table 5. Individuals holding various types of employment (manufacturing, firefighting, healthcare, law enforcement, and other occupational groups) have facial features that differ significantly than those in construction. Employees in the manufacturing sector have significantly larger bigonial breadth, head breadth, head circumference, head length, face length, nasal root breadth, and nose protrusion and smaller bitragion coronal arc and nose lengths. Firefighters have smaller space in between their eyes and a narrower jaw; however, they are taller, with longer and wider noses and larger crown dimensions than construction workers. Healthcare workers have shorter noses. However, seven other dimensions are significantly larger than construction workers: bitragion coronal arc, face width, head breadth, minimal frontal breadth, face length, nasal root breadth, and height. The final distinct category of employment is law enforcement. These employees have features that are smaller than construction workers, including three arc measurements, face width, nasal root, and nose breadth. Nevertheless, they are taller, with larger head circumference, head length, and nose protrusion.

When comparing PC1 values (i.e. overall face size characteristics) between occupational groups, no differences were observed between construction workers and those in firefighting or law enforcement. Firefighters and those employed in law enforcement had the same overall face size as construction workers. The PC1 was significantly larger for those employed in manufacturing and healthcare than those in construction (AC = 1.5 and 2.0, respectively). When comparing PC2 values (face shape characteristics), the trend is vice versa. Firefighters and those employed in law enforcement had larger PC2 values than those in construction (AC = 1.1 and 1.0, respectively). While manufacturing and healthcare workers had similar face shape as construction workers.

Weight and height. With each 10 kg increase in weight, every dimension increased significantly, except for nose length. The first PC increased significantly (AC = 3.4), indicating that with increased weight, the overall size of the face increases. The second PC decreased significantly (AC = 0.6), resulting in a wider overall face and wider shorter nose characteristics. With each height increase of 100 mm, all but three dimensions revealed significantly different values (face width, nasal root breadth, and nose breadth). Bigonial breadth and neck circumference significantly decreased, while all remaining dimensions significantly increased. The first principal component reveals that with increased height, the overall size of the face increases (AC = 1.1) and PC2 increases, resulting in a face with features that are longer and narrower (AC = 2.0).

DISCUSSION

The anthropometric instruments used to collect facial dimensions are reliable to ±0.5 mm. Compounding the limits of the instrumentation to the inherent inter- and intra-rater reliability of anthropometric data collection and the practical significance for the dimensions equates to an AC ≥ 2 mm. The remaining portion of the Discussion will pertain to results that were practically significant, not the statistically significant values introduced in the Results section.

When observing practically significant differences between groups, for the 10 dimensions specific to respirator fit (Table 4b), one can discern that gender and ethnicity dominate facial characteristic differences between groups. Females significantly differ from males for 9 of 10 dimensions. Nasal root breadth for females is not significantly different from males. Female bigonial breadth, face width, and face length are smaller than the male values by 7.6, 6.0, and 5.3 mm, respectively. The six remaining dimensions are smaller than male values by 0.3 mm–4.7 mm. This data reveal that women in general have smaller faces than males and the corresponding PC1 and PC2 values confirm this relationship.

Depending on which ethnic group is compared to the baseline Caucasian group, 7 of 10 dimensions differ at a practically significant level. Face length is a key feature related to respirator fit and practically significant differences occur across racial/ethnic groups for African-Americans and Hispanics, having longer face lengths than Caucasian by 2.7 and 2.8 mm, respectively. The other ethnic group was not significantly different from baseline. Both nose

protrusion and interpupillary breadth are correlated to respirator fit, and nose breadth has been found to affect the respirator fit. Oestenstad *et al.* (1990) suggests that nasal dimensions need to be taken into consideration when fitting a person for a respirator or when developing fit test panels. The AC of nose protrusion from baseline is significant for African-Americans (AC = −2.3 mm) and the other ethnic group (AC = −2.1 mm). The only ethnic group to differ from baseline for interpupillary breadth was African-Americans (AC = 3.4 mm). The AC for nose breadth was practically significant for all racial/ethnic groups and ranged from 2.7 mm for Hispanic workers to 7.6 mm for African-Americans workers.

In the past, panels have been formulated using face length and face width for the full-facepiece respirator and face length and lip length for the half-mask respirator. Lip lengths were significantly longer only for African-Americans (AC = 3.7 mm). There has been correlation between half-mask respirator fit factor and anthropometric measurements: face length, lip length, face width, and nasal root breadth (Liau *et al.*, 1982). There are also some facial measurements that are good predictors of other facial measurements (Zhuang *et al.*, 2007). Research done by Han and Choi (2003) showed that face width, bitragion–menton arc (bitragion chin arc), and nose protrusion should be the primary consideration for half-mask respirator design. Face width was practically significant between Hispanics and Caucasians (AC = 3.6 mm) and the other ethnic group and baseline (AC = 5.0 mm). Bitragion chin arc was found to be practically significant for all ethnic groups. The AC for African-Americans, Hispanic, and other workers were 9.4, 8.3, and 8.5 mm, respectively. African-Americans and other workers have shallower noses, with their nose protrusion dimensions smaller than Caucasians by 2.3 and 2.1 mm, respectively.

The current study identified statistically significant differences ($P < 0.05$) in anthropometric facial measurements among four racial/ethnic groups, by gender and age in US workers. This is important inasmuch as facial dimensions and configurations affect respirator sizing and airflow characteristics within the respirator (Rebar *et al.*, 2004). For example, it has been suggested that long narrow faces (long face length and narrow face width) as observed in Caucasian males and females in this study could result in increased turbulence (Johnson and Berlin, 1973) and thus more resistance inside respirator masks (Rebar *et al.*, 2004). Similarly, shorter lip lengths (as noted in Caucasian and other groups in

the current study) have been suggested as increasing turbulent flow within respirators because they might allow available oxygen to bypass the mouth or contribute to a build up of carbon dioxide inside the mask. Increased resistance inside a respirator could have an effect on the amount of time and the rate at which one could perform work while wearing a respirator (Rebar *et al.*, 2004). Relatively few prior studies have addressed the issue of racial/ethnic differences in facial anthropometric measurements in the context of respiratory protection (Brazile *et al.*, 1998; Kim *et al.*, 2003; Zhuang *et al.*, 2004) and different conclusions have been reached. Kim *et al.* (2003), in a study of 110 university students, noted significant differences in facial anthropometric dimensions between Koreans and Caucasians with respect to respirator fit, whereas Brazile *et al.* (1998) found no such differences in their study of male and female Caucasians, African-Americans, and Mexican-Americans measured for 14 facial anthropometric dimensions (total 186 subjects); however, both these studies used relatively small sample sizes.

In the current study, African-Americans had statistically significant higher mean values than Caucasians for a majority of facial measurements (13 of 19 facial measurements). The data lend some support to the findings of McConville (1976) who examined data from multiple military anthropometric studies and noted that African-American males had nasal root breadth, nose breadth, and lip length measurements that exceeded those of Caucasian males by upward of 10%. In the current study, nose breadth (AC = 7.7 mm) and lip length (AC = 3.7 mm) measurements were all significantly greater in African-Americans than Caucasians. Similarly, McConville (1976) noted differences of at least 5% between African-American males and Caucasian males with respect to interpupillary breadth, nose protrusion, lip length, and face length and at least a 10% difference in nose breadth and lip length between Caucasian and African-American women. In the present study, interpupillary breadth (AC = 3.4 mm), nose protrusion (AC = −2.3 mm), lip length (AC = 3.7 mm), face length (AC = 2.7 mm), and nose breadth (AC = 7.6 mm) were all significantly different between Caucasian and African-American workers.

An unexpected finding from this analysis was that there were significant differences in anthropometric values between construction workers and other occupational groups even after gender, ethnicity, and age were taken into consideration. Arc measurements, head length, and head circumference were

significantly different, which could be critical to the design of protective headgear used in various industrial settings. Facial features relevant to respirator fit are not practically significant except when comparing face length and jaw width of firefighters to construction workers. A limiting factor to this analysis was the sample size distribution in cells across various occupations. For instance, the healthcare workers were predominantly female and males composed the majority of construction workers. In addition, sample sizes for non-Caucasian females were limited with only one or two subjects in a given age and occupational group. Even though the statistical analysis accounted for gender, ethnicity/race, and age, a sample pool containing cells with equal numbers of subjects may yield different results.

Since significant differences were observed between gender, race, age, and occupational groups, further studies are needed to determine if respirator fit test panels for some ethnic groups or occupational groups are beneficial to standards developers and respirator designers. For example, Oestenstad et al. (2008) conducted a study to determine how well the newly developed NIOSH bivariate panel would incorporate the facial dimensions of 100 African-American male respirator wearers compared to the Los Alamos full-facepiece and half-mask panels. They found that 98% of the subjects' dimensions fell within the NIOSH bivariate panel, while only 84% fell within the Los Alamos full-facepiece panel and 83% fell within the half-mask panel. Although >95% of each race or occupational group may fall within the NIOSH bivariate panel, how they distribute among panel cells is still important to know.

Respirator effectiveness relies heavily upon respirator fit, which is, in turn, impacted in large degree by facial skin surfaces and dimensions. Facial dimension changes are influenced by such factors as endocrine function, dentition, scarring, age, gender, beard growth, surgery, and sudden weight loss or gain, to name but a few (Roberge et al., 2006). As worldwide immigration continues to increase, the minority populations of many industrialized nations will continue to experience growth. Minority populations will increasingly take their place in the US work force, and some of them will join the estimated 3 million persons currently employed in occupations that require respiratory protection (U.S. Bureau of Labor Statistics/NIOSH, 2003; Zhuang and Bradtmiller, 2005). Therefore, it is incumbent upon personal protection equipment researchers and design engineers to address all design and use issues that can potentially impact respirator efficacy.

CONCLUSIONS

Statistically significant differences in facial anthropometric dimensions ($P < 0.05$) were noted between males and females, all racial/ethnic groups, and the subjects who were at least 45 years old when compared to workers 18–29 years of age. This study also revealed that race/ethnicity is second to gender for impacting face size and shape characteristics. Our data suggest that (i) gender is a critical variable in determining respirator sizing schemes; (ii) employers with significant numbers of African-Americans and Hispanics in occupations requiring respiratory protection may need to ensure adequate supplies of, and accessibility to, larger sizes of respirators; and (iii) future designs of respirator face seals, internal respirator surface, and volume can benefit from occupational anthropometric studies. These findings can potentially have significant economic and distribution impact for respirator purchasers and suppliers and may enhance the safety and health of persons who rely upon and use respirators with new designs and sizing schemes.

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