The Role of Normal Nasal Morphological Variations from Race and Gender Differences on Respiratory Physiology

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Abstract

Objectives: To identify anatomical and airflow-induced relationships based on nasal morphological variations due to inter- and intra-racial differences and gender. Design: Subject-specific reconstruction of the nasal airway anatomy was created from computed tomography images in 16 subjects: 4 subjects from each ethnic group (Black, East Asian, Caucasian, and Latino) comprising of 2 males and 2 females. Volume, surface area, nasal index, airflow rate, and nasal resistance were measured to determine the role of normal nasal morphological variations due to race and gender differences on these variables. Results: Bilateral nasal airspace surface area (p=0.0499) and volume (p=0.0281) were significantly greater in male subjects than in females. Median (Interquartile Range; IQR) surface area was 218.83cm^{2} (IQR=29.42 cm^{2}) for males and 190.08cm^{2} (IQR=19.77cm^{2}) for females, and 20.88cm^{3} (IQR=3.72 cm^{3}) versus 18.02cm^{3} (IQR=3.06cm^{3}) for males and female's nasal volumes, respectively. Nasal volume was greatest in East Asians (Median=20.38cm3, IQR=4.58cm3), while Latinos had the greatest surface area (Median=219.70cm2, IQR=29.56cm2). East Asian and Black females had a larger average nasal index than their male counterparts, while Latino and Caucasian males had a larger average nasal index than their female counterparts. Caucasians had the highest median pressure at 12.55Pa (IQR=6.19Pa) and highest median nasal resistance at 0.050Pa.s/ml (IQR=0.025Pa.s/ml), while East Asians had the lowest for both variables. Conclusions: Our findings indicate that there exist anatomical variabilities based on race and gender. However, these variabilities may not significantly influence nasal respiratory functions.

ABSTRACT

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Conclusions: Our findings indicate that there exist anatomical variabilities based on race and gender. However, these variabilities may not significantly influence nasal respiratory functions.

Key Points

1. Computational modeling was used to investigate race and gender differences on normal nasal physiology.
2. Our findings suggest that East Asians had the largest median nasal volume, while Caucasians had the smallest median nasal volume. However, Blacks demonstrated the largest variability in the distribution of nasal cavity volume.
3. As expected, males had a larger distribution of nasal cavity volume than females. Furthermore, Caucasian females had the smallest average nasal volume, whereas Black males had the largest average nasal volume.
4. Blacks had the largest median nasal index and Caucasians had the smallest median nasal index. In terms of gender differences, males had a slightly larger median nasal index than females.
5. Median nasal resistance was lowest for East Asians and highest among Caucasians; however, nasal resistance between both genders was not significantly different.

Introduction

The normal human nose is distinguished by common inter- and intra-individual nasal morphological variations. These variations such as nasal cycle, nasal vestibule phenotypes, and nasal index can influence objective description of normal nasal airflow profile.[1-4] Briefly, the asymmetry of nasal airflow as characterized by a random, reciprocal shift in nasal patency due to temporal periods of congestion and decongestion of the mucosa in both nasal passages is described as nasal cycle.[1] Prior studies reported between 21% and 80% of individuals experience some aspect of nasal cycling.[3, 5, 6]

Ramprasad and Frank-Ito[7] identified another feature of natural variation in the nasal anatomy based on nasal vestibule morphological shapes, which were classified as Notched, Standard, and Elongated. Reported findings suggest global airflow patterns and resistance in the nasal cavity were unaffected by the different morphological shapes, but local airflow resistance and air conditioning performance were found to be greatly impacted by these morphological variations.[3, 7] Consequently, it was postulated that the manifestation of these distinct normal nasal vestibule phenotypes may be associated with the fact that the human nasal airway naturally response to localized constrictions by inducing corresponding physiological response on other regions of the airway in order to maintain natural ventilation conditions.[3, 7, 8]

Variations in nasal morphology is also thought to have been due to human adaptation to diverse climatic environments.[2, 9-11]Changes in nasal shape reflect the conditions for respiration in an environment as adaptations were made in order to provide more efficient conditions to maximize respiration.[2, 9] These differences in human noses due to geographic adaptations are often characterized by nasal index.[7, 12, 13] A systematic review study performed by Leong and Eccles showed no consistent evidence supporting the idea that differences in nasal shape and size based on ethnic descent influence physiology.[12]

Although the predicted link between race and nasal morphology is supported by anthropological studies recording relationships between climate and nasal function, more studies need to be done to understand how gender differences within and between races influence nasal physiology. Little is known on the associations of nasal anatomy and function based on race and gender. Nonetheless, it has been established that males exhibit larger nasal cavities volumes and longer and narrower nasal floors than females of a similar body size.[4, 14, 15]

Thus, the purpose of the present study is to use computational modeling to investigate additional relationships between nasal morphological variations due to inter- and intra-racial differences and gender.

Methods

Ethical Considerations

This retrospective study was approved by an Institutional Review Board for Clinical Investigations under protocol Pro00102005. Consent from the subjects were obtained on enrollment of the study in accordance with the approval protocol.

Study Cohort

Sixteen adult subjects with computed tomography (CT) images were selected based on a search of university medical records. The subjects are from four racial/ethnic groups: African Americans (Blacks); East Asians; Caucasians; and Latin Americans. The study cohort is made up of eight males and eight females, four subjects from each racial/ethnic group comprising of two males and two females. Inclusion criteria were normal nasal anatomy; high resolution spiral CT scan images; and no clinical evidence of nasal and/or sinonasal disease. CT images were examined by an attending radiologist and an otolaryngologist to ensure the nasal cavities of all subjects selected for this work had radiographic evidence of normal nasal cavity.

Nasal Reconstruction and Mesh Generation

Computational modeling was used to generate the results. DICOM images of each subject were de-identified and imported into the imaging analysis and segmentation software, Avizo Lite 2019.3 (Thermo Fisher Scientific, Waltham, Massachusetts). Three-dimensional (3D) reconstructions of each subject's main nasal passage were digitally created, and the paranasal sinuses excluded since this study focuses on the main nasal cavity. Avizo Lite 2019.3 was also used to calculate the volume (V) and surface area (SA) of each subject's nasal passage. The nasopharynx was excluded from these calculations as it has been reported that perception of nasal patency during respiration was more evident from nostrils to choana than nostrils to posterior end of nasopharynx.[16] The surface area-to-volume ratio (SAV) was calculated by dividing the SA by the V.

Reconstructed models were exported in stereolithography format from Avizo and into the CAD and mesh generating software package, ICEM-CFD 19.0 (ANSYS, Canonsburg, PA). Planar inlet surfaces near the nostrils and an outlet surface at the nasopharynx were created. Next, roughly 4 million unstructured tetrahedral elements and three-layer prism elements were generated in each model's computational domain. Mesh refinement analysis was not done based on prior work based on prior work by our group.[17] Mesh quality analysis was performed to confirm the aspect ratio for the hybrid mesh was properly smoothed to prevent poor elements quality from impacting the accuracy of the numerical simulation.

Numerical Simulation

Steady-state, laminar inspiratory airflow was simulated in the nasal cavities using the CFD software package Fluent 19.0 (ANSYS, Inc., Canonsburg, PA) to mimic physiologic inhalation conditions at 15L/min. The no-slip, stationary wall boundary condition was imposed on the nasal wall. A "pressure-inlet" condition at the nostrils with gauge pressure set to zero. A "mass-flow-rate" condition at the outlet to target 0.000301kg/s (15L/min).

Computed Quantities of Interest

To determine the patency of each nasal cavity, nasal resistance (NR) was calculated as [?]P/Q (Pa.s/mL) where [?]P is bilateral pressure drop from nostrils to choana, and Q is bilateral volumetric flow rate. In addition, as described in Patki and Frank-Ito[2], nasal index was calculated as $100 \times NW \div NH$, where NWis nasal width and NH is nasal height. Lastly, statistical comparisons were made between the genders, using the nonparametric Wilcoxon Rank Sum test and significance (alpha=0.05), to test that the difference in their median values was zero.

Results

Boxplots of bilaterally computed nasal airspace surface area (SA), volume (V), and surface area-to-volume ratio (SAV) were compared across East Asians, Blacks, Latinos, Caucasians, and between genders. Across the races (Figure 1A), median (IQR=interquartile range) SA was greatest among Latinos at 266.02cm2 (IQR=25.03cm2), while East Asians had the smallest median SA at 187.50cm2 (IQR=23.33cm2). The median SA comparison by gender presented in Figure 1B showed that males had a significantly greater (p= 0.0499) SA than females; 218.83cm2 (IQR=29.42cm2) versus 190.08cm2 (IQR=19.77cm2).

With regards to nasal airway volume, East Asians and Caucasians had the largest and smallest median volume, respectively; 20.38cm3 (IQR=4.58cm3) for East Asians and 18.63cm3 (IQR=5.19cm3) for Caucasians (Figure 1C). Interestingly, as evidenced by IQR values and whisker lengths in Figure 1C, Blacks demonstrated the largest variability (IQR=8.38cm3) in the distribution of nasal cavity volume. Similar to Figure 1B, box plots in Figure 1D showed that males had a significantly larger (p=0.0281) distribution of nasal cavity volume than females; 20.88cm3 (IQR=3.72cm3) versus 18.02cm3 (IQR=3.06cm3).

The median SAV for all four racial groups indicated (Figure 1E) that Caucasians and Latinos had relatively larger SAV at 10.97cm^{-1} (IQR=1.50cm^{-1}) and 10.72cm^{-1} (IQR=2.77cm^{-1}), respectively, compared to the respective median SAV for East Asians and Blacks; 9.12cm^{-1} (IQR=3.01cm^{-1}) and 9.40cm^{-1} (IQR=3.26cm^{-1}). Figure 1F showed females with slightly larger median SAV than males at 10.85cm^{-1} (IQR=2.44cm^{-1}) and 9.74cm^{-1} (IQR=2.82cm^{-1}), respectively, albeit not significantly larger than males (p=0.44).

On average, nasal cavity SA for females in each race/ethnicity was smaller than their respective male counterparts (Figure 2A); however, average SA for Black females (195.67cm2) was marginally smaller than Black males (197.60cm2). With a difference of 29.56cm2, the Caucasian race had the largest difference between average SA for females and males. The group with the smallest average SA, across all races and genders, was East Asian females (172.74cm2), while the largest average SA was Caucasian males (227.36cm2).

Average nasal cavity volume (Figure 2B) largely followed a similar pattern as SA (Figure 2A), with the exception of Latinos where females had a larger average nasal volume than their male counterpart. Overall, Caucasian females had the smallest average nasal volume at 16.58cm3, while Black males had the largest (26.40cm3; Figure 2B). Results for SAV were completely reversed from those of nasal volume – except for Latinos, average SAV values among females of the other races/ethnicities were respectively larger than their male counterparts (Figure 2C). Caucasian females and Latino males overall had the largest SAV at 11.93cm^{-1} and 12.28cm^{-1} , while Black males had the smallest (7.48 cm^{-1}).

Blacks had the largest median nasal index of 95.82 (IQR=3.08), whereas Caucasians had the smallest median nasal index of 72.46 (IQR=0.89; Figure 3A). Latinos and East Asians followed with a median of 82.59 (IQR=8.84) and 78.33 (IQR=6.62), respectively. In Figure 3B, males had a slightly larger nasal index than females with respective median values of 80.98 (IQR=13.86) and 79.25 (IQR=20.12).

Figure 3C described comparisons between race and gender for nasal index. East Asian and Black females had a larger average nasal index than their male counterparts, while Latino and Caucasian males observed the opposite trend. It should be noted that the difference in average nasal index between Caucasian males and females may be considered negligible. Overall, Black females had the largest average nasal index (97.05) and Caucasian females had the smallest average nasal index (72.24).

Among the races, Caucasians had the greatest median nasal airflow pressure of 12.55Pa (IQR=6.19Pa), followed by Blacks at 11.47Pa (IQR=7.79Pa); while East Asians had the smallest median nasal airflow pressure of 5.65Pa (IQR=7.45Pa; Figure 4A). For nasal airflow pressure comparison by gender, males and females had approximately the same median nasal airflow pressure values (males=10.88Pa, females=10.11Pa, p= 0.7984); nonetheless, males had larger variability with an IQR of 9.21Pa, compared to females (IQR = 5.14Pa; Figure 4B).

Median nasal resistance was highest among Caucasians at 0.050Pa.s/ml (IQR=0.025Pa.s/ml; Figure 4C). Blacks and Latinos followed with nearly identical median nasal resistance of 0.046Pa.s/ml (IQR=0.032Pa.s/ml) and 0.043Pa.s/ml (IQR=0.016Pa.s/ml), respectively. East Asians had the lowest nasal resistance (median=0.023Pa.s/ml, IQR=0.030Pa.s/ml). Next, nasal resistance between males and females were not significant difference (p=0.7984). Both genders had nearly identical median nasal resistance values of 0.044Pa.s/ml (IQR=0.04Pa.s/ml) for males and 0.041Pa.s/ml (IQR=0.02Pa.s/ml) for females (Figure 4D).

Additionally, average pressure for males was larger than females of their respective race in all races except for East Asians (Figure 5A). Caucasian and East Asian females had very similar pressure values around 12.50Pa. East Asian females had a much greater pressure than East Asian males with a difference of 6.95Pa. Across all races and genders, Black males had the largest pressure at 14.65Pa, while East Asian males had the smallest pressure at 5.64Pa.

Similar to Figure 4, Figure 5 revealed that nasal airflow pressure and nasal resistance generally followed identical patterns, except among Blacks where females on average had lower nasal airflow pressure (Figure 5A) but higher nasal resistance (Figure 5B) than their male counterparts. Latino males, East Asian females, and both Caucasian genders had nearly similar nasal airflow pressure of about 13Pa (Figure 5A), and nasal resistance value around 0.05Pa.s/ml (Figure 5B). Across all races and genders, Caucasian males had the largest nasal resistance at 0.052Pa.s/ml and East Asian males had the smallest nasal resistance at 0.023Pa.s/ml (Figure 5B).

Discussion

The present study focused on relationships between nasal morphological variations due to inter- and intra-racial differences and gender, which differs from previously published studies by our group investigating nasal morphological variations.[2, 18] Unlike this study that categorizes nasal index by subjects' race/ethnicity with gender, and gender separately; Patki and Frank-Ito[2] explored the relationship between nasal index and CFD simulated airflow-related variables, such as nasal resistance, wall shear stress, and heat flux.

Although Keeler et al.[18] modeled deposition patterns of individuals across the same four race/ethnic groups as the present study, as well as briefly reported results of SAV ratio, nasal resistance and nasal index across races/ethnicities; the present student conducted an in-depth analysis of both anatomical and airflow-related variables in the same race/ethnic groups with gender as a factor. Additionally, Keeler et al.[18] included the paranasal sinuses in their CFD models while the present study excluded the paranasal sinuses are they have negligible effects on physiological functions pertaining to the main nasal cavities.

Nasal index results are in agreement with reports on climate-related variation in human nose, suggesting that individuals that evolved from colder and drier climates tended to have smaller nasal index than individuals from warmer and more humid climates.[2, 12, 18, 19] Results in this study pertaining to nasal index and gender are consistent with those previously reported by Ravichandran et al.[20] In their paper, Ravichandran and colleagues found that nasal index is a reliable parameter for the estimation of gender difference, noting that the average value of nasal indices of South Indian males was greater than South Indian females.[20] Additionally, in a study examining the nasal index of the Kosovo Albanian population, males had a significantly higher nasal index than females ($p < 0.001$).[21] While similar conclusions can be made with the Caucasian population from the present study, it should be noted that the difference in median nasal index between Caucasian males and females was 0.66. Additionally, when comparing nasal index and gender by race, East Asian and Black females had larger average nasal index than their male counterparts.

The current literature is sparse regarding the relationship between nasal resistance and race/ethnicity. Keeler et al.[18]reported that average nasal resistance for African Americans and Caucasians were lowest and highest, respectively. Other studies have reported no significant differences in nasal resistance between African descents and Caucasians.[19, 22, 23] Babatola measured nasal resistance of African descents from Nigeria and concluded that nasal resistance in this population was similar to those of Caucasians and Asians.[22] Calhoun et al. and Ohki et al.[19, 23] also arrived at similar conclusions in their studies. Our results suggest that median nasal resistance was highest among Caucasians, followed by Blacks before Latinos, and East Asians had the lowest median nasal resistance values. Nonetheless, it should be noted that the IQR values for Blacks and East Asians were particularly larger than those of Caucasians and Latinos, implying there could be possible overlap among the groups, which may indicate non-significant differences among groups.

Our findings indicate females have a larger nasal resistance than males. This trend was seen within every race except for Caucasians when comparing between nasal resistance and race and gender. A study conducted by Warren et al.[24] revealed no significant difference in resistances for males and females with normal nasal anatomy. However, Ren et al.[25] reported that mean nasal resistance in males were significantly lower than females among a cohort of healthy subjects in China.

The main limitation from the present study pertains to our relatively small sample size. Although there were 16 subjects, each race had 4 subjects, and after further stratification by race and gender, there were 2 subjects per group. In conclusion, this study investigated the relationships between normal nasal morphological variations due to inter- and intra-racial and gender differences in subject-specific nasal airway models from 16 subjects across 4 racial groups. Findings from the present work indicate that there is an association between normal nasal anatomical variabilities across race and gender. However, these variabilities may not discriminate proper functioning of the nasal cavity across race and gender.

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Figure Legend

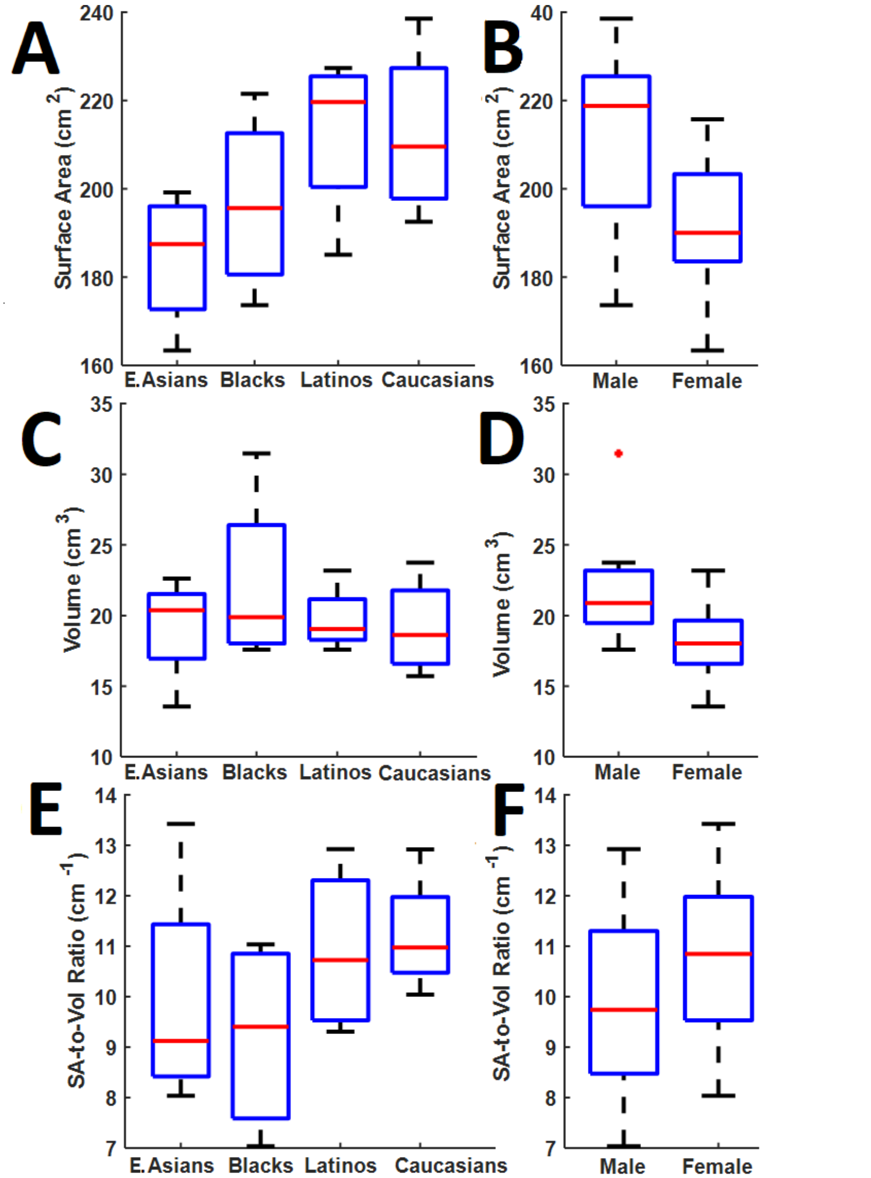
Figure 1: Nasal cavity surface area by (A) Race and (B) Gender. Nasal cavity volume by (C) Race and (D) Gender. Nasal cavity surface area-to-volume ratio by (E) Race and (F) Gender.

Figure 2: Nasal cavity quantification by race and gender for (A) Surface area, (B) Volume, and (C) Surface Area-to-Volume Ratio.

Figure 3: Nasal index quantification by (A) Race, (B) Gender, and (C) Race and gender.

Figure 4: Nasal pressure by (A) Race and (B) Gender. Nasal resistance by (C) Race and (D) Gender.

Figure 5: Nasal cavity results by race and gender for (A) Pressure, and (B) Resistance.


A
B
C
D
E
F
Surface Area (cm 2)
Volume (cm 3)
SA-to-Vol Ratio (cm -1)
240
220
200
180
160
40
35
30
25
20
15
10
14
13
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11
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9
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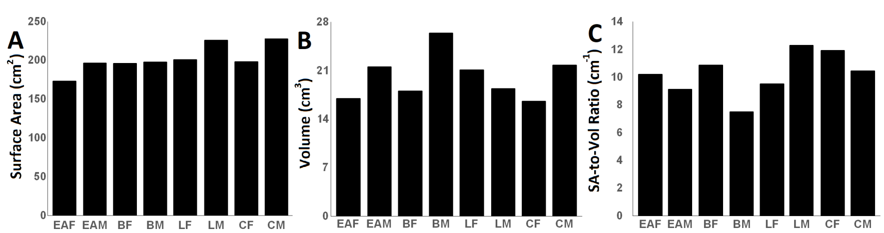
7
E.Asians Blacks Latinos Caucasians
Male Female


A
B
C
Surface Area (cm2)
Volume (cm3)
SA-to-Vol Ratio (cm-1)
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200
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100
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7
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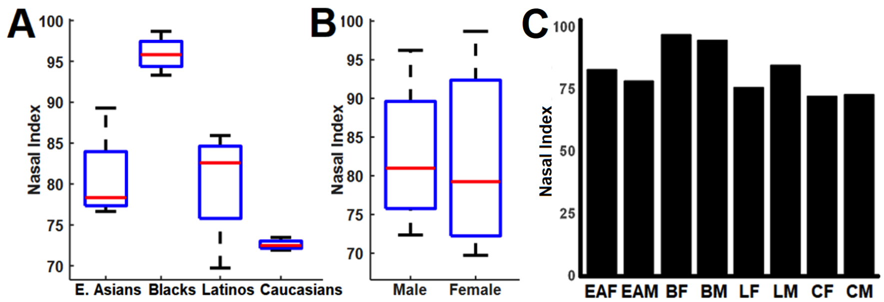
A
Nasal Index
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95
90
85
80
75
70
E. Asians Blacks Latinos Caucasians
B
Nasal Index
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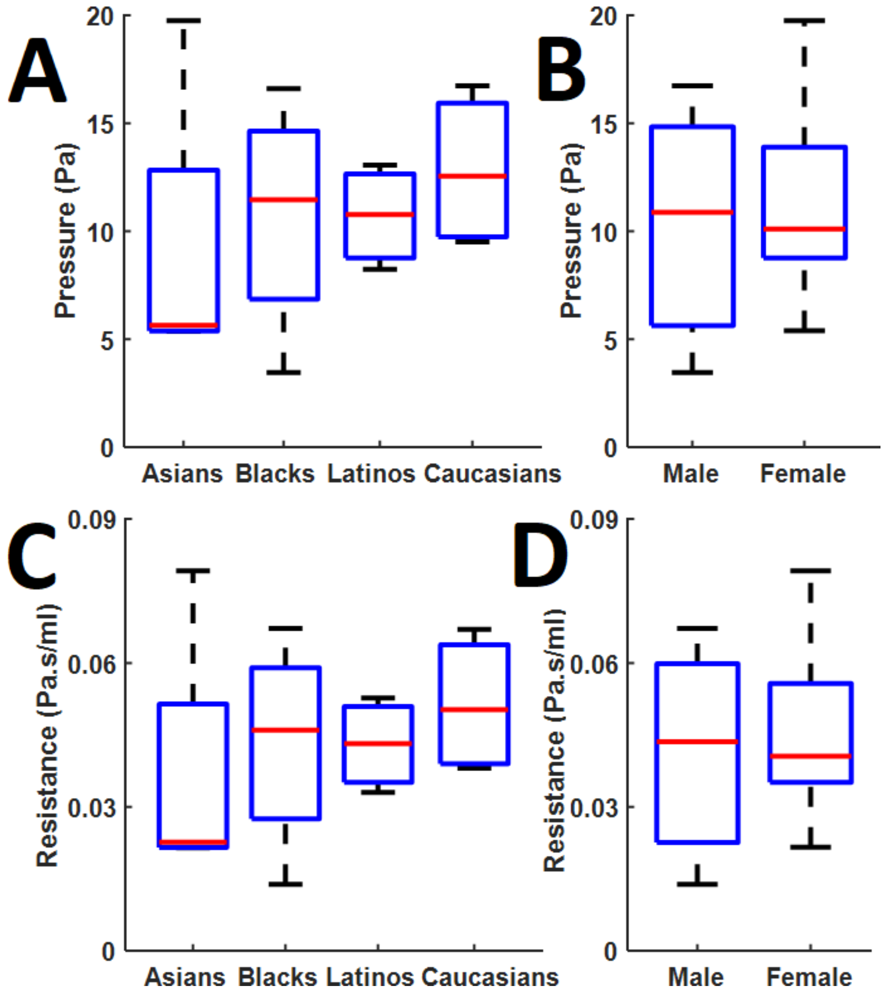
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Pressure (Pa)
20
15
10
5
0
Asians Blacks Latinos Caucasians
B
Pressure (Pa)
Male Female
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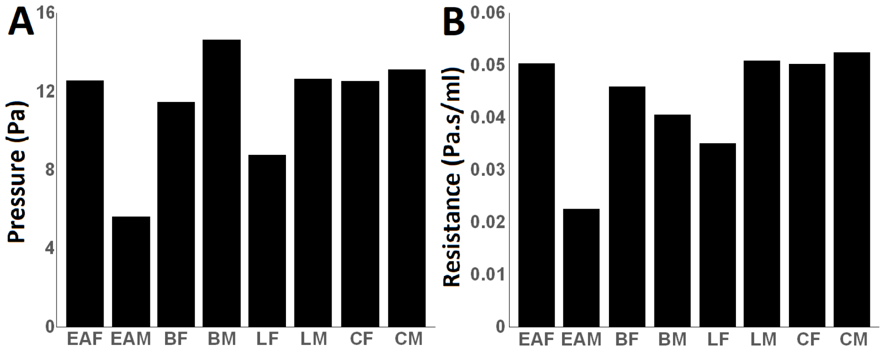
Resistance (Pa.s/ml)
Male Female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Resistance (Pa.s/ml)
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0.04
0.03
0.02
0.01
0
EAF EAM BF BM LF LM CF CM