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Nasal contribution to breathing with exercise: effect of race and gender

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Bennett, William D., Kirby L. Zeman, and Annie M. Jarabek. Nasal contribution to breathing with exercise: effect of race and gender. *J Appl Physiol* 95: 497–503, 2003. First published April 11, 2003; 10.1152/japplphysiol.00718.2002.—Because the nose acts as a filter to prevent penetration of toxic particles and gases to the lower respiratory tract, the route of breathing, oral vs. nasal, may be an important determinant of toxicant dose to the lungs. Using respiratory inductance plethysmography and a nasal mask fitted with flowmeter, we measured the nasal contribution to breathing at rest and during exercise (to 60% maximum workload) in healthy young adults (men/women = 11/11 and Caucasian/African-American = 11/11). We found that the nasal contribution to breathing is less during submaximal exercise in the Caucasians vs. African-Americans (e.g., at 60% maximum workload, mean nasal-to-total ventilation ratio = 0.40 ± 0.21 and 0.65 ± 0.24, respectively, $P < 0.05$). This difference is likely due to the African-Americans' ability to achieve higher maximal inspiratory flows through their nose than the Caucasians. Men also had a lesser nasal contribution to breathing during exercise compared with women. This is likely due to greater minute ventilations at any given percentage of maximum workload in men vs. women.

oronasal breathing; exercise ventilation; nasal resistance

THE MODE OF BREATHING, ORAL vs. nasal, is an important determinant of deposited dose of inhaled particles and gases to the lungs (1). The nose can act as an effective filter to prevent penetration of particles and gases to the lower respiratory tract. Gases that are very water soluble or reactive, e.g., SO_2, aldehydes, organic esters, and ozone, can be extracted in the nose by up to 95% during resting breathing (18, 32). Very large (>5-μm aerodynamic diameter) and very small (<0.01 μm) particles are deposited very efficiently in the nose by inertial impaction and diffusion, respectively, during nasal breathing (8, 33). In addition, the nose effectively conditions inspired air to near body temperature and 98–100% relative humidity before it enters the lungs (9). The ability of the nose to condition ambient air in these ways serves as a protective mechanism against toxicity to the lower respiratory tract.

Ventilation rate is a key determinant of both inhaled particle deposition and gas uptake in the respiratory tract. Ventilation rate is linked to activity, e.g., with exertion or strenuous activity, people who typically breathe through their nose will augment their nasal ventilation and also breathe through their mouth (oronasal breathing). The mode of breathing, i.e., via the mouth or nose, dramatically alters airflow dynamics in the upper respiratory tract and influences particle deposition and gas uptake. The capability of the nose to filter or condition inspired air is diminished as airflow is diverted from nasal to mouth breathing during exercise. The level of ventilation at which this switch from nasal to oronasal breathing occurs has been previously referred to as the "oronasal switching point" (21). A number of studies, however, have shown that oronasal breathing occurs at resting ventilation in some individuals (3, 7, 14). Characterizing the ventilation level and variability across individuals for the relative contribution of nasal to total breathing is critical to the construction of ventilation activity patterns for accurately constructing the airflow apportionment (nasal or mouth) at various ventilation rates associated with different activities. Ventilation activity patterns (e.g., 10-h rest, 8-h sitting, 5-h light work, and 1-h heavy exercise in a 24-h day) are beginning to be used in risk assessment to link exposure profiles to internal dose for more accurate dose-response assessment. For example, Snipes et al. (29) recently used different ventilatory patterns to illustrate that age, gender, and disease state may be important determinants of susceptibility to inhaled particles. Characterization of the variability in ventilation is an important consideration to determine the magnitude of the intrahuman variability uncertainty factor applied in inhalation risk assessment (15).

The level of exercise at which the oronasal switching point occurs and the relative contributions of oral vs. nasal breathing at rest and during exercise have been studied by a number of investigators (3, 7, 14, 21, 22, 25, 27, 31). The physiological determinants of the relative contributions to nasal and oral breathing during exercise are still not well understood. Presumably,

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nasal resistance (R_{nose}) to airflow should determine the relative work of breathing between nasal and mouth breathing and thus the switch from nasal to oronasal breathing during exercise (27). Schultz and Horvath (27) showed that, within an individual, nasal work of breathing was the most repeatable variable at crossover to oral breathing in subjects and thus a potential candidate for determining the initiation of oral augmentation during exercise. Many previous studies, however, have not found good correlations between R_{nose} and the switch to oronasal breathing (7, 14, 25) between individuals, perhaps because the maximal inspiratory flow through the nose (MIF_{nose}) may be determined by more than R_{nose} as measured under resting flow conditions (5, 6, 24). Bridger and Proctor (5, 6) suggested that collapsibility of the nasal valve (referred to as alar collapse) plays a role in MIF_{nose} that is independent of R_{nose} downstream of the collapse point (i.e., flow-limiting segment). After noting that the few African-American subjects studied were able to achieve higher maximum nasal flow rates, they further suggested that differences in nasal structure associated with race (10, 11) may translate into different maximal flow capacities.

Similarly, modest gender differences in nasal structure have also been observed (10) and may translate into gender-dependent oronasal switching with exercise. More importantly, on average, women have lower maximal physical work capacities (PWC_{max}) and associated ventilation rates. Thus, at a given work effort (as $\%PWC_{max}$), women might be expected to have a greater nasal contribution to breathing than men. Gender differences in these relative contributions of nasal breathing are important for assessing relative risks associated with inhaled toxicants.

The purpose of our study was to determine whether the relative contribution of nasal and oral breathing during light-to-moderate exercise is dependent on race or gender in adults. Previous studies of this type have not addressed race as a factor in oronasal breathing. Neither have they reported data comparing gender in terms of relative contribution of nasal breathing as a function of work effort. Second, we attempted to better elucidate how parameters of nasal physiology, i.e., resistance and MIF_{nose}, might determine the relative contributions to nasal and oral breathing during exercise.

METHODS

A group of 11 Caucasian (6 men/5 women) and 11 African-American (5 men/6 women) healthy, nonsmoking adults, age 18–31 yr, were studied. The subjects had no smoking history, no history of lung disease, and no recent history of acute respiratory infection or viral illness within the previous 4 wk. A few subjects reported seasonal nasal allergies and associated rhinitis but were asymptomatic during the time of study. Forced expiratory volume in 1 s and forced vital capacity were determined for each subject by spirometry. Informed consent was obtained from each volunteer; the study had the approval of the University of North Carolina Committee on the Protection of the Rights of Human Subjects.

A measure of each subject's predicted maximum exercise capacity on a cycle ergometer (2) was determined. While being monitored by a three-lead ECG, subjects performed graded submaximal exercise at three increasing workloads (in W) while maintaining a pedal rate of 60–70 rpm. Each workload trial lasted 5 min. The maximum of the three workloads did not exceed a heart rate of 170 beats/min. By linear extrapolation of the workload-heart rate relationship to each subject's age-related predicted maximum heart rate (2, 21), the subject's PWC_{max} was determined.

On a subsequent study day, the relative contributions of oral vs. nasal breathing were measured at rest and during incrementally graded submaximal exercise on the cycle ergometer (10% increments from 0–60% PWC_{max} for each subject) (21, 22). The subject was fitted with a nasal mask (Respironics, Murrysville, PA) (approximate dead space of 60 ml) that was similar to that used in pulmonary sleep laboratories and modified to allow insertion of a mass flowmeter (Korr Medical Technologies, Salt Lake City, UT) to detect nasal airflow (21, 22). Total ventilation ($\dot{V}_E$) was determined by respiratory inductance plethysmography (Respitrace) (calibrated by spirometry) (4, 7, 30). The Respitrace bands (abdomen and rib cage) were fixed to the subject's torso with adhesive tape to minimize slippage during exercise. The changes in inductance of these bands with expansion and contraction were calibrated to spirometry for each subject, according to the procedure of Tobin et al. (30). Oral airflow was determined as the difference between total (Respitrace) and nasal (nasal mask). Subjects maintained a 60- to 70-rpm pedal rate at each 10% increment of effort for 2 min. Flow characteristics during the last 30 s of each 2-min period were recorded at 20-Hz sampling rate and analyzed on a MacIntosh computer by using Superscope (GW Instruments) data-acquisition and analysis software. To calibrate volumes obtained from respiratory inductance plethysmography with the nasal flowmeter, we compared both signals to a volume signal from a spirometer through which the subject rebreathed (4) postexercise via the nose only with the obstructed mouthpiece (mouth plug) in place. We did this calibration postexercise so that the subject would be as unbiased as possible with regard to nasal vs. oral breathing during the exercise session. In a few initial, pilot subjects (data not included here), we found that having them perform measurements with nose mask and mouth plug in place before the exercise session created a bias in oronasal breathing. These subjects thought they were to try to breathe through their nose during the exercise session with the nasal mask in place but without a mouth plug. We tried to remove any bias toward nasal or oral breathing by letting the subjects relax with the Respitrace and nasal mask in place for a few minutes before beginning their graded exercise and asking them not to think about their breathing during the session.

Immediately after measurements of oral-nasal breathing during exercise (within 15 min), measurements of airway resistance in the body plethysmograph were made while the subject panted through a mouthpiece (with nose plug) and then through the nasal mask (with mouth plug) described above (23). R_{nose} was then determined as the absolute difference between the mouthpiece and nasal mask measure of total airway resistance. The assumption associated with this technique is that the mouth adds very little to the measure of total airway resistance. This technique for measuring R_{nose} has been shown to correlate well with posterior rhinometry (23), is easier for subjects to perform, and is more realistic to conditions associated with exercise breathing (i.e., cyclic panting) than posterior rhinometry (i.e., constant inspired flow). Also, after the exercise session (within 15 min postex-

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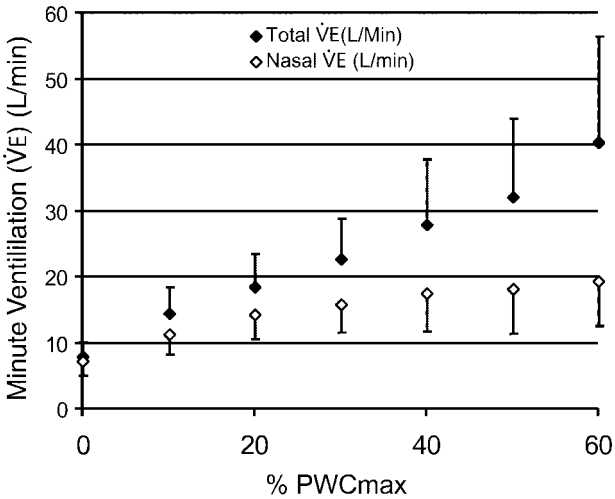

Fig. 1. Mean total (+SD) and nasal ventilation (−SD) [minute ventilation ($\dot{V}E$); in l/min] as a function of relative workload [percentage of maximal physical work capacities (%PWC_{max})].

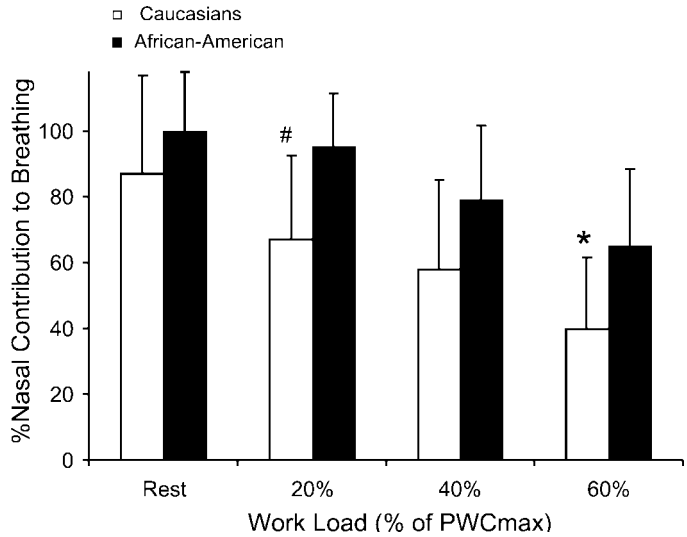

Fig. 2. Percent nasal contribution to breathing at rest and at 20, 40, and 60% PWC_{max} for Caucasians vs. African-Americans. Values are means ± SD. Significant difference: $^{\#}P < 0.01$ and $^{*}P < 0.05$.

ercise), we had subjects perform maximal inspiratory flow maneuvers via their nose by slowly exhaling to near residual volume and then rapidly inhaling through their nose at maximal effort with the nose mask and mouth plug in place (24). MIF_{nose} associated with these maneuvers was determined as the peak flow for each maneuver.

Statistical analysis. Group comparisons, i.e., Caucasians vs. African-Americans and men vs. women, for all variables reported were made by independent sample *t*-test. As an exploratory analysis, we also performed multivariate backward and forward stepwise regression for %nasal contribution at rest and at 20, 40, and 60% PWC_{max}, considering the following independent variables: race, gender, R_{nose}, MIF_{nose}, and $\dot{V}E$ at that workload. Due to our limited data set, we did not consider interactions between variables for this exploratory analysis. Statistical criteria for a variable to enter and stay in the stepwise model was set at $P = 0.15$.

RESULTS

Figure 1 shows the average total and nasal $\dot{V}E$ as a function of %PWC_{max} in all subjects studied. $\dot{V}E$ increased linearly with increasing workload to 60% PWC_{max}, whereas nasal ventilation increased more slowly with increasing workload.

Table 1 summarizes the racial comparison of subject exercise capacities, $\dot{V}E$, and lung and nasal function. Only forced vital capacity and MIF_{nose} were significantly different between the two groups. There was a tendency for R_{nose} to be less in the African-Americans vs. the Caucasians ($P = 0.08$). R_{nose} tended toward a negative correlation with MIF_{nose} ($r = -0.41$, $P = 0.06$). Figure 2 illustrates the nasal contribution to breathing (in %$\dot{V}E$) as a function of workload in %PWC_{max} for Caucasians and African-Americans. At 20 and 60% PWC_{max}, the Caucasians had significantly less nasal contribution to breathing than African-Americans ($P < 0.01$ and 0.05, respectively). There was also a tendency toward a racial difference at 40% PWC_{max} ($P = 0.06$).

Table 2 summarizes the gender comparison of subject exercise capacities, $\dot{V}E$, and lung and nasal function. The women had a significantly less PWC_{max} compared with the men and, as a result, also had a lesser $\dot{V}E$ at 60% PWC_{max}. Figure 3 illustrates the nasal contribution to breathing (in %$\dot{V}E$) as a function of workload (in %PWC_{max}) for men vs. women. At 40% PWC_{max}, the men had significantly less nasal contribution to breathing than women ($P < 0.05$). There was also a tendency toward a gender difference at 20% PWC_{max} ($P = 0.06$). Because there was a gender difference in work capacity, we also compared the men and women at a given workload. All subjects had a

Table 1. *Racial comparisons*

	Caucasian	African-American
Men/Women, no.	6/5	5/6
Age, yr	22 ± 3	22 ± 4
Maximum work, W	173 ± 39	154 ± 68
$\dot{V}E$ at rest, l/min	7.6 ± 1.6	8.2 ± 2.7
$\dot{V}E$ at 60% maximum, l/min	41.0 ± 14.1	40.9 ± 18.7
Forced vital capacity, liters	5.0 ± 0.9	4.2 ± 0.9*
R_{nose}, $cmH_2O \cdot s \cdot l^{-1}$	2.72 ± 1.81	1.61 ± 0.88
MIF_{nose}, l/s	2.1 ± 0.6	2.8 ± 1.0*

Values are means ± SD. $\dot{V}E$, minute ventilation; R_{nose}, nasal resistance; MIF_{nose}, maximal inspiratory nasal flow. *Significant difference, $P < 0.05$.

Table 2. *Gender comparisons*

	Women	Men
n	11	11
Age, yr	22 ± 2	22 ± 4
Maximum work, W	125 ± 37	201 ± 42*
$\dot{V}E$ at rest, l/min	6.9 ± 0.9	8.9 ± 2.6†
$\dot{V}E$ at 60% maximum, l/min	30.7 ± 7.4	51.2 ± 16.3‡
Forced vital capacity, liters	4.0 ± 0.8	5.2 ± 0.8‡
R_{nose}, $cmH_2O \cdot s \cdot l^{-1}$	1.89 ± 1.32	2.44 ± 1.69
MIF_{nose}, l/s	2.2 ± 0.8	2.7 ± 0.9

Values are means ± SD; *n,* no. of subjects. Significant differences: $^{*}P < 0.001$; $^{\dagger}P < 0.05$, $^{\ddagger}P < 0.005$.

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Fig. 3. Percent nasal contribution to breathing at rest and at 20, 40, and 60% PWC_{max} for women vs. men. Values are means ± SD. *Significant difference, $P < 0.05$.

workload at or near 50 W during their exercise (a workload associated with ~20% PWC_{max} in men and 40% PWC_{max} in women), at which women and men had a $\dot{V}E$ of 22.1 ± 2.4 (SD) and 23.5 ± 5.3 l/min respectively [not significant (NS)]. At this workload, women had a nasal contribution to breathing of 79 ± 21% compared with 67 ± 28% for men (NS).

The results of multivariate stepwise regression analysis for %nasal contribution to breathing at rest showed no significant variables at the $P = 0.15$ level. The same analysis at 20% PWC_{max} showed significance for *1*) $\dot{V}E$ at this workload ($P = 0.001$) and *2*) race ($P = 0.007$; $r^2 = 0.62$ for the regression). Similarly, at 40% PWC_{max}, the regression analysis showed significance for *1*) $\dot{V}E$ at this workload ($P < 0.001$) and *2*) race ($P = 0.028$; $r^2 = 0.62$ for the regression). Finally, at 60% PWC_{max}, the regression analysis showed %nasal contribution to breathing dependence on *1*) $\dot{V}E$ at this workload ($P < 0.001$) and *2*) race ($P = 0.003$; $r^2 = 0.59$ for regression). Neither R_{nose} nor MIF_{nose} was a significant predictor of %nasal contribution to breathing at any exercise level.

Figure 4 illustrates the relationship between $\dot{V}E$ and the %nasal contribution at 40% and 60% PWC_{max}. For comparison to previous work, the "switching point" reported by Niinimaa et al. (21), $\dot{V}E$ = 35 l/min, is delineated. Below $\dot{V}E$ = 35 l/min, there is considerable variation in %nasal contribution to breathing (30–100%), with African-Americans clearly having a greater nasal contribution than Caucasians. Above $\dot{V}E$ = 35 l/min, the %nasal contribution drops to <40% in all of the Caucasians, whereas four of the African-Americans maintain %nasal contributions of >40%.

DISCUSSION

As in previous studies (3, 7, 14, 21, 22, 25, 31), our laboratory has shown that the nasal contribution to breathing decreases with increasing exercise (Fig. 1). Consequently, the air entering the lower respiratory tract is less conditioned and filtered of inhaled toxicants than it is otherwise (1, 9), thus subjecting the lower respiratory tract to potential insult. Others have also shown an average 50% nasal contribution to $\dot{V}E$ at a mean $\dot{V}E$ of 40 l/min (7, 22, 31). Whereas our data and that of others suggest that the %nasal contribution plateaus as total $\dot{V}E$ increases, absolute nasal ventilation rates may continue to rise, reaching mean peak values of 40 l/min (25). Unlike some previous findings (21, 22), we did not find a distinct switching point for a change from nasal to oronasal breathing; rather, subjects generally tended to gradually increase their oral contribution to breathing as exercise levels increased. Nevertheless, a comparison of the switching point of Niinimaa et al. (21) (35 ± 10 l/min) with our nasal contributions and ventilation rates (Fig. 4) shows that, for ventilation rates >30 l/min, all subjects had nasal breathing that falls <90% of total. It is also true that, above the switching point of 35 l/min (Fig. 4), except for two outliers, all subjects' nasal contribution to breathing fell <50%. However, below that ventilation rate there was considerable variability in the nasal contribution to breathing (i.e., 30–100%). Other studies (7, 14) have also found a more variable switching between nasal and oronasal breathing as we have found here. Some of the differences between studies may be due to different measurement techniques but also may be due to the "blindedness" of the subjects toward the test's objectives. We found in pilot studies that, if subjects thought we wanted them to breathe through their nose (based on posttest questioning), they were more likely to maintain nasal breathing solely until reaching a switching point, where, despite their best efforts, they needed to orally supplement their breathing. In fact some subjects who were less fit than others never achieved ventilation rates where switching occurred.

We also found that the degree of nasal breathing at rest was correlated with %nasal contribution to breathing during exercise. The best simple regression be-

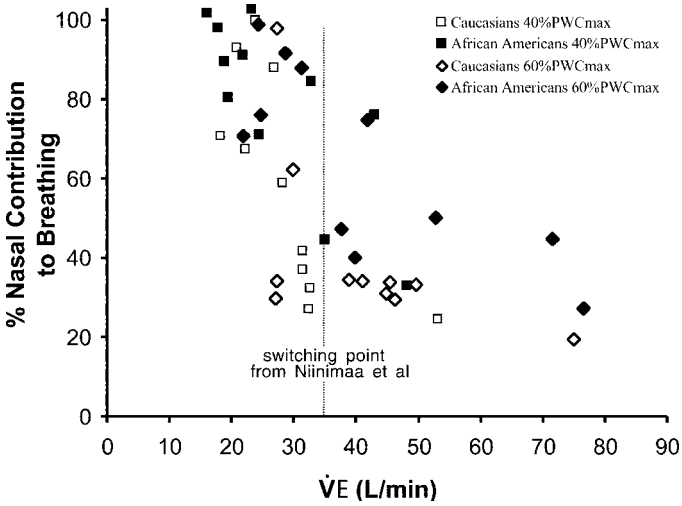

Fig. 4. Relationship between $\dot{V}E$ rate and the percent contribution of nasal breathing at 40% and 60% PWC_{max}. The "switching point" from Niinimaa et al. (21) is shown for comparison.

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tween resting nasal contribution and nasal contribution during exercise occurred at the 20% PWC_{max} level ($r = 0.51$, $P < 0.05$) and diminished by 60% PWC_{max} ($r = 0.38$, NS). So while there may have been some effect of subject's baseline nasal contribution at rest, this effect or relationship was not significant at the higher workloads and thus could not explain the racial differences seen as exercise progressed. Furthermore, there was no significant racial difference in nasal contribution to breathing at rest ($P = 0.20$). We chose to characterize nasal contribution to breathing as a function of relative (14, 21, 22) rather than absolute (7, 25) workload for reasons associated with risk assessment. Because individuals have variable fitness levels, they will generally exercise at their own capacities (or fraction of their PWC_{max}). Thus the breathing patterns for these relative workloads should be considered when attempting to model and/or assess risk associated with inhaled toxicants. Using relative workloads to compare nasal contribution to breathing as a function of race did not affect our findings, because the PWC_{max} and $\dot{V}E$ at any relative workload were similar between African-Americans and Caucasians. However, the same comparison between men and women was affected because the latter had significantly lower PWC_{max} and thus lower ventilation rates at a given $\%PWC_{max}$.

Previous investigators have not distinguished their subjects by race and their associated differences in nasal function. We have shown here that African-Americans have a greater nasal contribution to breathing with exercise compared with Caucasians. This difference was greatest as exercise level increased. Whereas there was only a tendency for R_{nose} to be less in the African-Americans compared with Caucasians (Table 1), there was a clear difference in the MIF_{nose}, with African-Americans able to achieve 33% higher maximal nasal flows. This was true, despite their having significantly smaller vital capacities (Table 1) than Caucasians (18). Figure 4 shows that, after switching to oronasal breathing, most African-American subjects were maintaining higher levels of %nasal contribution than most of the Caucasians. Two African-Americans had nasal contributions of 75% at $\dot{V}E$ as high as 40 l/min (Fig. 4).

A clear relationship between either MIF_{nose} (which differed by race) or R_{nose} and nasal contribution to breathing was not evident in our study. This may be due, in part, to the fact that both MIF_{nose} and R_{nose} were measured immediately postexercise, at rest. Whether or not we obtained a true reflection of R_{nose} during the exercise period is open to question. First, we measured an average R_{nose} (inspiratory and expiratory) over the flow range of ± 0.5 l/s postexercise. The resistance at different phases of the breathing cycle may vary and be important for determining maximal nasal ventilation during exercise. For example, Shi et al. (28) showed hysteresis in the inspiratory resistance during hyperpnea, i.e., lesser R_{nose} during increasing vs. decreasing inspiratory flow. They further showed that voluntary flaring of the nostrils reduced the hysteresis and overall R_{nose}. The degree to which their results with voluntary hyperventilation can be extrapolated to the exercise condition is not clear, however. Second, total R_{nose} at a given flow rate is known to be reduced with exercise, depending on the workload (12). We tried to capture the R_{nose} associated with each subject's exercise state by measuring it immediately postexercise, in each case within 15 min. However, it is not known how much change in R_{nose} occurred for each subject in association with the exercise protocol. Nor were we able to ascertain the degree to which each subject maintained nasal dilatation postexercise. We chose not to measure preexercise R_{nose} and MIF_{nose} so that subjects would be as naive as possible with regard to oronasal breathing during the exercise protocol (discussed in METHODS). Future studies using other measures or indexes of R_{nose} that do not require use of the nasal mask, e.g., acoustic rhinometry, may allow for these pre- and postmeasures while also not biasing subjects with regard to their oronasal breathing during the exercise protocol.

Our findings suggest that Caucasians may be at greater risk for inhalation of toxic gases and particles than African-Americans because of their lower nasal contribution to overall breathing. However, it may also be that there are racial differences in nasal efficiencies for removing these gases and particles. Some recent studies suggest that this may in fact be the case for inhaled particles. Kesavanathan et al. (16, 17) attempted to link specific nasal characteristics with total and regional particle deposition in the adult nose. They showed that nasal particle deposition efficiency for 2–6 μm was increased with decreased minimal cross-sectional area of the nasal passages and increasing ellipticity of the nostrils, with the latter being significantly greater in Caucasians than in African-Americans. Others have shown that the minimal cross-sectional area of the nasal passages is significantly larger in African-Americans than Caucasians as well (10). So the advantage of greater nasal contribution to breathing observed by us may be offset by a less efficient nasal filtering capacity in African-Americans. Differences in nasal efficiency associated with race require further study, especially for gaseous pollutants and conditioning of inspired air.

Our finding of lesser nasal contribution to breathing with exercise for men vs. women is likely due to the different ventilation rates (due to different workloads) at each level of exercise (Table 2). The regression analysis showed that, at each level of exercise, %nasal contribution to breathing was most significantly associated with $\dot{V}E$. From a risk assessment perspective, the men may be at greater risk (i.e., more susceptible) to inhalation of toxic gases and particles compared with women exercising at similar effort levels. On the other hand, when we matched workload (at ~50 W) and $\dot{V}E$ between men and women, there was not a significant gender difference in nasal contribution to breathing. We also found no gender difference in nasal function (Table 2), which is supported by other measures of internal nasal structure as well (10).

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A few models have incorporated values for nasal ventilation fractions to predict particle deposition in the lower respiratory tract (13, 20, 26). In each case, model inputs were based on the previous study of Niinimaa et al. (22) and do not take into account racial or gender differences discussed here. For example, the most recent International Commission on Radiological Protection model (13) incorporated fixed fractions of nasal ventilation for all adults, either "normal augmenters," i.e., those who breathe nasally at rest, or "habitual mouth breathers," depending on their type of activity (e.g., sleep, sitting, light exercise, and heavy exercise). For the light-exercise condition, normal augmenters and habitual mouth breathers were predicted to have a nasal ventilation fraction of 1.0 and 0.4, respectively. Our data (e.g., Figs. 2 and 3) may provide input of more realistic average nasal ventilation fractions in the adult population that will vary as a function of race and gender. For example, a comparison of the light-exercise condition (20% PWC_{max}) in African-Americans vs. Caucasians shows nasal fractions of ~1.0 and 0.7 (Fig. 2) that can be used to predict respiratory tract deposition differences between these two groups. However, to be accurate, these models must also consider the relative scrubbing efficiency of the noses as a function of race and gender.

Conclusion. Like others, we have shown that the contribution of nasal breathing to $\dot{V}_E$ diminishes with increasing exercise effort. However, we have also found that nasal ventilation during exercise varies as a function of both race and gender. African-Americans have a greater nasal contribution to breathing during exercise than Caucasians. It may be that this interracial difference is due to the former's ability to achieve greater maximal flow rates through their nose, although this dependence requires further investigation. At relative exercise efforts (i.e., as a %maximum work capacity), the women also had a greater nasal contribution to breathing during exercise than men. This gender difference is explained by the fact that the women achieved lower $\dot{V}_E$ than men at a given percentage of their maximum work capacity. Because oral augmentation during exercise was shown to be a function of $\dot{V}_E$, the women did not need to augment their breathing orally until much later in their relative work effort. These racial and gender-related differences in route of breathing during exercise may be important for determining relative risks of individuals to environmental or occupational exposures of potentially toxic gases or particulate matter.

DISCLOSURES

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REFERENCES

1. **Anderson I and Proctor DF.** The fate and effects of inhaled materials. In: *The Nose: Upper Airway Physiology and the Atmospheric Environment*, edited by Proctor DF and I Anderson. New York: Elsevier Biomedical, 1982, p. 423–443.
2. **Astrand P and Rodahl K.** Evaluation of physical work capacity on the basis of tests. In: *Textbook of Work Physiology*. New York: McGraw Hill, 1977, p. 333–365.
3. **Becquemin MM, Bertholon JF, Bouchiki A, Malarbet JL, and Roy M.** Oronasal ventilation partitioning in adults and children: effect on aerosol deposition in airways. *Radiat Prot Dosimetry* 81: 221–228, 1999.
4. **Bennett WD, Zeman KL, and Kim CS.** Variability of fine particle deposition in healthy adults: effect of age and gender. *Am J Respir Crit Care Med* 153: 1641–1647, 1996.
5. **Bridger GP.** Physiology of the nasal valve. *Arch Otolaryngol* 92: 543–553, 1970.
6. **Bridger GP and Proctor DF.** Maximum nasal inspiratory flow and nasal resistance. *Ann Otol Rhinol Laryngol* 79: 481–488, 1970.
7. **Chadha TS, Birch S, and Sackner MA.** Oronasal distribution of ventilation during exercise in normal subjects and patients with asthma and rhinitis. *Chest* 92: 1037–1041, 1987.
8. **Cheng KH, Cheng YS, Yeh HC, Guilmette RA, Simpson SQ, Yang YH, and Swift DL.** In vivo measurements of nasal airway dimensions and ultrafine aerosol deposition in the human nasal and oral airways. *J Aerosol Sci* 27: 785–801, 1996.
9. **Cole P.** Modification of inspired air. In: *Respiratory Function of the Upper Airway*, edited by Mathew OP and Sant'Ambrogio G. New York: Dekker, 1988, p. 415–445.
10. **Corey JP, Gungor A, Nelson R, Liu X, and Fredberg J.** Normative standards for nasal cross-sectional areas by race as measured by acoustic rhinometry. *Otolaryngol Head Neck Surg* 119: 389–393, 1998.
11. **Cottle MH.** The structure and function of the nasal vestibule. *Arch Otolaryngol* 62: 173–181, 1955.
12. **Dallimore NS and Eccles R.** Changes in human nasal resistance associated with exercise, hyperventilation and rebreathing. *Acta Otolaryngol (Stockh)* 84: 416–421, 1977.
13. **International Commission on Radiological Protection.** Human respiratory tract model for radiological protection. *Ann ICRP* 24: 1–482, 1994.
14. **James DS, Lambert WE, Mermier CM, Stidley CA, Chick TW, and Samet JM.** Oronasal distribution of breathing at different ages. *Arch Environ Health* 52: 118–123, 1997.
15. **Jarabek AM.** Interspecies extrapolation based on mechanistic determinants of chemical disposition. *Human Ecol Risk Assess* 1: 641–662, 1995.
16. **Kesavanathan J, Bascom R, Laube B, and Swift DL.** The relationship between particle deposition in the anterior nasal passage and nasal passage characteristics. *J Aerosol Med* 13: 17–23, 2000.
17. **Kesavanathan J, Bascom R, and Swift DL.** The effect of nasal passage characteristics on particle deposition. *J Aerosol Med* 11: 27–39, 1998.
18. **McDonnell WF and Seal E.** Relationships between lung function and physical characteristics in young adult black and white males and females. *Eur Respir J* 4: 279–289, 1991.
19. **Medinsky MA and Bond JA.** Sites and mechanisms for uptake of gases and vapors in the respiratory tract. *Toxicology* 160: 165–172, 2001.
20. **Miller FJ, Martonen TB, Menache MG, Graham RC, Spektor DM, and Lippman M.** Influence of breathing mode and activity level on the regional deposition of inhaled particles and implications for regulatory standards. *Ann Occup Hyg* 32, *Suppl* 1: 3–10, 1988.
21. **Niinimaa V, Cole P, Mintz S, and Shephard RJ.** The switching point from nasal to oronasal breathing. *Respir Physiol* 42: 61–71, 1980.
22. **Niinimaa V, Cole P, Mintz S, and Shephard RJ.** Oronasal distribution of respiratory airflow. *Respir Physiol* 43: 69–75, 1981.

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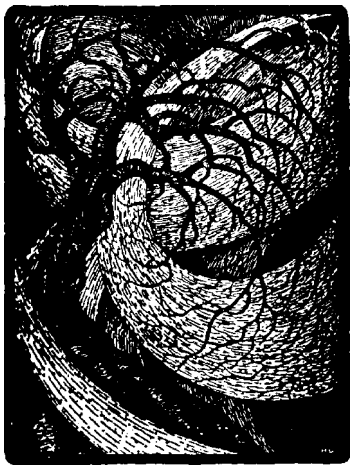
23. **Nolte D and Luder-Luhr I.** Comparing measurements of nasal resistance by body plethysmography and by rhinomanometry. *Respiration* 30: 31–38, 1973.
24. **Phagoo SB, Watson RA, and Pride NB.** Use of nasal peak flow to assess nasal patency. *Allergy* 52: 901–908, 1997.
25. **Saibene F, Mognoni P, Lafortuna CL, and Mostardi R.** Oronasal breathing during exercise. *Pflügers Arch* 378: 65–69, 1978.
26. **Salma I, Balashazy I, Hofmann, and Zaray G.** Effect of physical exertion on the deposition of urban aerosols in the human respiratory system. *J Aerosol Sci* 33: 983–997, 2002.
27. **Schultz EL and Horvath SM.** Control of extrathoracic airway dynamics. *J Appl Physiol* 66: 2839–2843, 1989.
28. **Shi Y, Seto-Poon M, and Wheatley JR.** Hysteresis of the nasal pressure-flow relationship during hyperpnea in normal subjects. *J Appl Physiol* 85: 286–293, 1998.
29. **Snipes MB, James AC, and Jarabek AM.** The 1994 ICRP66 human respiratory tract dosimetry model as a tool for predicting lung burdens from exposures to environmental aerosols. *Appl Occup Environ Hyg* 12: 547–554, 1997.
30. **Tobin MJ, Chadha TS, Jenouri G, Birch SJ, Gazeroglu HB, and Sackner MA.** Breathing patterns. 1. Normal subjects. *Chest* 84: 202–205, 1983.
31. **Wheatley JR, Amis TC, and Engel LA.** Oronasal partitioning of ventilation during exercise in humans. *J Appl Physiol* 71: 546–551, 1991.
32. **Yokoyama E and Frank R.** Respiratory uptake of ozone in dogs. *Arch Environ Health* 25: 132–138, 1972.
33. **Yu CP, Diu CK, and Soong TT.** Statistical analysis of aerosol deposition in nose and mouth. *Am Ind Hyg Assoc J* 42: 726–733, 1981.



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