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# Effects of nostril orientation on airflow dynamics, heat exchange, and particle depositions in human noses

Jinxiang Xi [a,*], JongWon Kim [b], Xiuhua April Si [c]

[a] School of Engineering and Technology, Central Michigan University, Mount Pleasant, MI, United States
[b] College of Engineering, University of Georgia, Athens, GA, United States
[c] Department of Mechanical Engineering, California Baptist University, Riverside, CA, United States

## HIGHLIGHTS

- Nostril orientation has a significant effect on ventilation and cellular-level depositions.
- Nostril orientation has a negligible effect on main flow turbulences and total depositions.
- The near-wall vertex structures exhibits significant dependence on the nostril angle, which significantly affects the near-wall stress and heat transfer rate.
- Retaining actual nostril angle is essential for reliable prediction of nose functions.

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## ABSTRACT

The orientation of the nostrils is thought to regulate airflow dynamics and associated functions of the nose. Previous studies have used different nostril orientations ranging from downward-directed (90°) to anterior-directed (0°). However, the influences of nostril orientation on nose functions have not yet been studied. The objective of this study is to systematically assess the influences of the orientation of the nostrils on airflow, heat exchange, and particle behaviors during inhalation by means of image-based modeling. Nose models with five different nostril angles were developed by modifying the vestibule of an anatomically accurate nose airway geometry reconstructed from magnetic resonance imaging. Large eddy simulations and a Lagrangian tracking model were used to simulate airflow dynamics and particle transport with a wide range of inhalation conditions (4–45 L/min) and particle sizes (1–20 μm). Results showed that nostril orientation exerted a significant impact on superior/inferior meatus ventilating and sub-regional and local depositions. The downward-directed nose model has the highest flow flux to the superior meatus and lowest flux to the nasal floor. The turbulence intensity inside the main flow is negligible; however, there are substantial vortex formations in the near-wall region. The anterior-directed nose model has the strongest near-wall vortices in the valve vicinity, which is coincident with the location of the highest wall shear stress and heat exchange, and has a close correlation with local particle deposition patterns. Results of this study indicate that the actual nostril angle should be preserved to reliably predict respiratory functions of a pathological/postsurgical nose, or the delivered doses of a topical intranasal delivery.



## 1. Introduction

A significant issue in evaluating the functions of human noses in conditioning and filtering inhaled air is to accurately determine the airflow dynamics. An accurate knowledge of airflow will also help to develop targeted drug deliveries, which convey medications to a specific area inside the nose, such as the olfactory mucosa or paranasal sinus. Several features of the nose anatomy have been claimed in regulating the inhaled airflows, thus adjusting the exchanges of air, heat, moisture, and inspired aerosols to the nasal mucosa [1–4]. These features include the orientation of the nostrils, the shape and size of the nasal valve, the height of the nasal sill, and the size and location of the turbinate relative to the internal nasal chamber, among others [2].

* Correspondence to: School of Engineering and Technology, Central Michigan University, 1200 South Franklin Street, Mount Pleasant, MI 48858, United States. Tel.: +1 989 774 2456; fax: +1 989 774 4900.
*E-mail address:* xi1j@cmich.edu (J. Xi).

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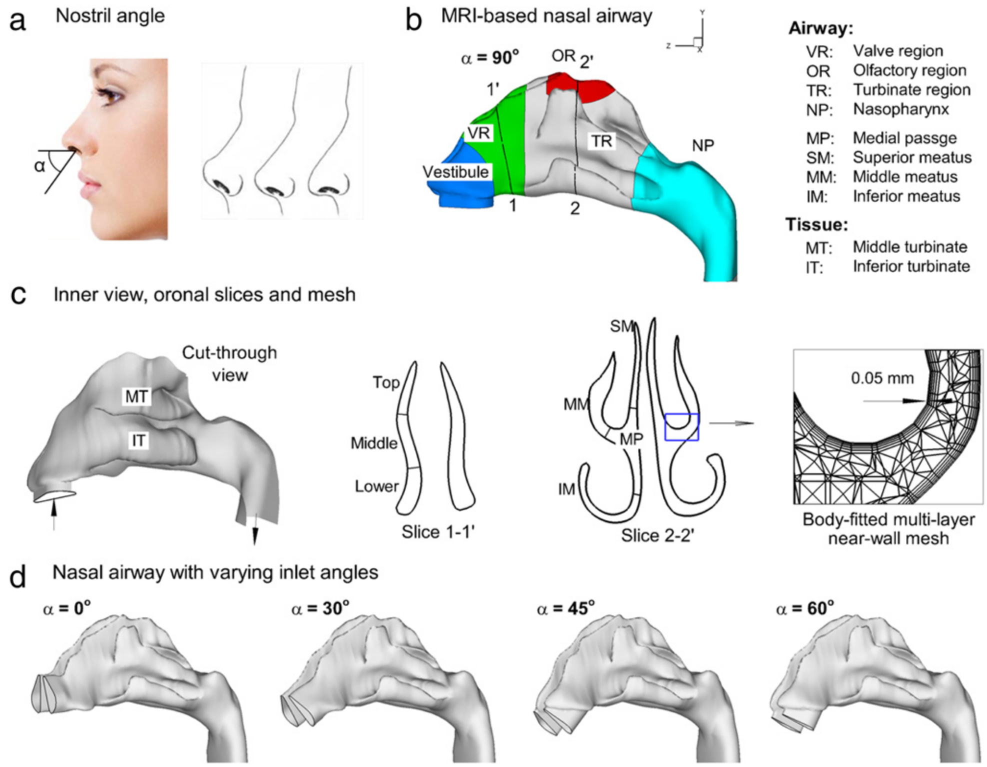


**Fig. 1.** Nasal airway models with different nostril angles. (a) Various nostril angles exist among humans of different races, subjects within a race, or even one subject at different ages. (b) MRI-based model with 90° nostril angle. The surface geometry was divided into five functional sections: vestibule, valve region (VR), turbinate region (TR), olfactory region (OR), and nasopharynx (NP). (c) The nasal valve region and turbinate region were further divided into three and four parts respectively according to their ventilation destinations. Body-fitted multilayer mesh was adopted with a height of 0.05 mm in the first near-wall layer. (d) Nasal airway models with inlet angle $\alpha$ of 0°, 30°, 45°, and 60°.

The orientation of the nostrils is a good example of ecogeographic adaptions in moderating the warming and humidifying of inspired airflows. It has been demonstrated that people living in the north tend to have protrusive noses with downwardly oriented nostrils, while people living in hot, humid environments tend to have flatter noses with more anteriorly oriented nostrils [5, 6]. However, even within an ethical group at the same geographic location, the nostril orientation varies. Churchill et al. [7] measured ten Caucasian subjects and reported a range of 31°–90° with a mean value of 62.9° (Fig. 1(a)). Moreover, as an individual grows from infancy to adulthood, the nostril direction also varies, typically from more anteriorly oriented to more downwardly oriented. In principle, the nostril orientation determines the degree to which the nasal vestibule-valve region resembles a straight versus a curved duct. In the 90° model, the inhaled airflow and particles must maneuver through a 90° bend before entering the horizontal turbinate region, generating a centrifugal force that drives the air and particles to the upper nose. In more anterior-oriented nose models, air and particles experience smaller centrifugal forces and tend to be more horizontal along the nasal floor.

Previous studies of airflows and particle depositions have used nasal models with a variety of nostril directions, ranging from horizontally (0°) to vertically (90°) oriented. Even though a majority of studies have utilized downwardly oriented nostrils [3, 8–14], nose models with a nostril angle other than 90° were common [15–20]. Some early studies neglected the realism of nostril orientation purely out of modeling and experimental convenience. Schreck et al. [17] developed a 3:1 scaled nose cast from magnetic resonance imaging (MRI) head scans that had a nostril angle of 65° for pressure measurements and flow visualizations. Naftali et al. [19] numerically investigated airflows in healthy and diseased human noses using an idealized two-dimensional model with a horizontal nostril opening. Kelly et al. [18] measured nasal airflow patterns using PIV in a scaled CT-based nose cast but with an anterior-directed nostril opening. They reported laminar flow regime, with high-speed flows through the nasal valve and nasal floor, and low-speed flows through the middle meatus and olfactory region. Hörschler et al. [15] used a nose model with a 45° nostril inlet and a 45° nasopharynx outlet to simulate the inspiratory and expiratory flows under resting conditions. More recent studies used human medical images to reconstruct nose models in order to preserve more details of the nostrils. Interestingly, most of these image-based models had a nostril angle of approximately 90° [3,9,10,21,22]. One exception was Segal et al. [20], who compared the bulk flows in four models and demonstrated significant intersubject differences. The four models had different nostril angles and were developed from MRI scans selected from 45 subjects in order to represent a range of nasal morphologies. In that study, Subject-A had a nostril angle of 90°, Subject-12 60°, subject-14 45° and Subject-18 30° [20].

Despite a plethora of *in vitro* and computational studies of human noses, investigations into the effect of the nostril angles are scarce. Churchill et al. [2] experimentally compared the influences of four anatomical factors (nostril angle, nasal sill height, valve area, and turbinate locations) on the turbulence intensities. It was observed that the nostril angle was the second key factor in inducing turbulent flows, whose impact was higher than the nasal valve and nasal sill height, and was smaller than the turbinate location. Another important issue associated with the differing nostril angles in different groups is the difficulties in comparing the results of these studies. The uncertainties incurred by the inconsistent nostril angles are still unclear and should be characterized in a quantitative manner.

The objective of this study is to quantify the effects of the nostril angle on airflow properties, wall shear stress, and particle depositions. Specifically, we aim to study the effects of the