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# Air conditioning analysis among human nasal passages with anterior anatomical variations

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ABSTRACT

A major functional role of the nasal cavity is air conditioning of the inspired environmental air to near alveolar conditions. It is well known that the anatomical disparities among nasal passages can change airflow patterns to a great extent. However, its effect on nasal air conditioning performance remains largely unexplored. This research investigated the nasal air conditioning performance among nasal models with distinct vestibule phenotypes, including subjects with and without vestibule notches. For the mass transfer, we used a two-film theory model to determine the species transport. Airflow patterns, heat and mass transfer between the inhaled airflow and the nasal mucosa were analysed and compared. Results showed that the nasal air conditioning performance is closely related to nasal passage structures. The anatomical variations, especially the geometry changes in the anterior vestibule region, can increase both heat and mass transfer rate between nasal mucous and respiratory air at the vicinity of the notched regions, while for other regions such as the anterior superior nasal cavity, the heat transfer is greatly reduced to even zero heat flux due to lack of active airflow passing.



## 1. Introduction

Nasal breathing is vital for most species, and one of the major functions of the nasal cavity is the conditioning (regulating the temperature and humidity) of the inspired environmental air to near alveolar conditions for the lungs. The nasal passages narrow at the nasal valve and widen as they reach the middle region, which is composed of wing-like structures (nasal turbinate) that emerge from the lateral walls. These slit-like structures of the nasal cavity provide exchange of heat and moisture as it assures close contact between the inhaled air and mucous membrane, and the arteriovenous anastomoses facilitates the heat exchange from arterial blood into inhaled air [1–4].

The process of the heating and moistening of respiratory air in the nasal cavity has been investigated both experimentally and numerically. Ingelstede and Toremalm [5] studied the heat transfer into simulated respiratory airflow based on a simplified straight tube that may mimic the trachea rather than the complex three-dimensional (3D) nasal geometry. Their results suggested that the degree of air-wall contact due to wall friction dictates the size of the boundary layer, and thereby, the degree of heat transfer to the inspired air. Nuckols et al. [6] built a realistic cast replica of the upper airway including nasal and mouth cavities as well as the trachea using transparent material. Convective heat transfer coefficients were computed from the temperature measurements during quasi-steady inspiratory and expiratory flows at hyperbaric conditions. Hanna and Scherer [7] investigated the mass transfer under a steady inspiratory airflow condition using an upper respiratory tract cast model, and provided the measured local mass transfer coefficients for the first time. *In vivo* measurements of temperature and air moisture within the nasal cavity in human subjects are limited due to the complex anatomy and the narrowed passageways, and the spatial and time resolution remains poor for published studies [8]. Furthermore, the experimental setup may cause unilateral obstruction of one nasal chamber and leads to increased concentration of water vapor and unrealistic water flux in the other side nasal passage [9,10].

Experimental challenges due to limited laboratory models and access to the complex 3D geometry of the nasal passageways encouraged the development of computational models with advancements of numerical algorithms and computer power enabling a more detailed approach to study nasal airflow dynamics [11–14] and its air conditioning capability [15,16]. Naftali et al. [17] performed a pioneering computational study in a nasal model

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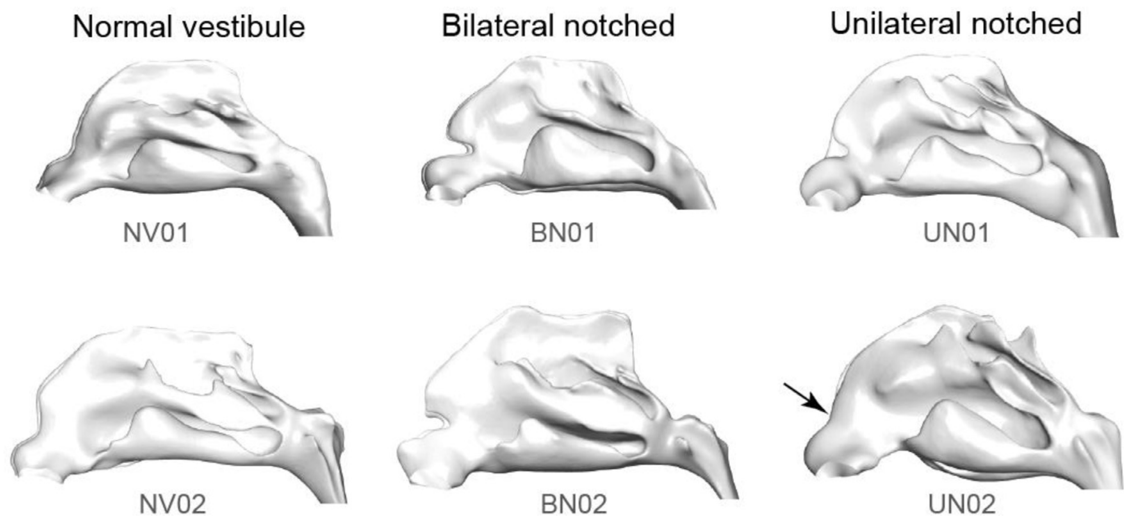


**Fig. 1.** Nasal models used in this study, which are classified into three groups: normal vestibule, bilateral notched, and unilateral notched. Please note, the vestibule notch of subject UN02 is located in the anterior right chamber, and it is not visible at the current left view.

with simplified transverse cross sections for inspiration under various ambient conditions. Their results demonstrated there is ample time for heat and water exchange in the nose-like model which includes essential features of adult human nasal cavity. Combining with medical imaging techniques such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), anatomically realistic 3D nasal geometries were implemented for air temperature distribution predictions [18–20]. Iwasaki et al. [21] performed numerical simulations of 23 young subjects to evaluate the improvement of nasal ventilation due to the rapid maxillary expansion treatment, with their results demonstrating capability for detecting flow obstructions. Nishimura et al. [22] numerically compared the air conditioning performance between human and primate subjects. Their results showed a horizontal straight flow of inhaled air in chimpanzees and macaques, contrasting with the upward and curved flow in humans.

Although the nasal airflow mechanics has been intensively studied, studies focusing on the effects of nasal morphological structure on nasal air conditioning performance remain inadequate. It is well known that airflow pathways are highly variable between individuals due to variation in nasal morphological structure. Research studies conducted by Thomson [23] and Yokley [24] classified the disparity in human nasal morphology using the nasal index, which is defined as the ratio between the width and height of the external nose [25]. Recently, Ramprasad and Frank-Ito [26] identified three distinct nasal vestibule phenotypes (standard, notched and elongated) across healthy and diseased nose subjects. Although disparities between nasal passages can influence nasal function, the different phenotype variation effect on air conditioning performance, nasal physiology and the presence of genetic characteristics behind the formation of each phenotype is unclear [26]. Wang et al. [27] numerically investigated the nasal airflow characteristics of patients with anterior nasal cavity stenosis, and compared pre- and postoperative airflow profiles. Their simulation results showed that curative surgery can help patients achieve balanced bilateral nasal ventilation and reduce flow resistance. However, nasal air conditioning including heating and moistening of respiratory air is not included. Additionally, past air-conditioning studies applied a constant surface wall temperature and constant water flux at the nasal walls. In this study we use species transport equation, and a two-film theory to determine the mass fraction of water on the nasal cavity wall

The main objective of this research is to investigate the air conditioning performance among nasal models with distinct vestibule phenotypes. This research offers insights into inspiratory airflow mechanics where air and nasal vestibule interaction with inhaled air plays a vital role in the heat and mass transfer process. The research findings can help otolaryngologists to address the influence of structural changes of the anterior nasal cavity and facilitate surgery assessment through pre- and post-operative treatment comparison.

## 2. Methods

In this study, realistic human nasal models were reconstructed from CT images, and basic model reconstruction and verification procedure can be referred from our previous studies [28–30]. In total, six nasal models were included in this study, and they were divided into three types based on vestibule phenotypes described in previous work [26]. The nasal vestibule lies directly posterior to the nostrils and is the initial point of interface between inhaled airflow/particles and main nasal passage. In this study the identified nasal vestibule architectural phenotypes were classified as normal, bilateral notched, unilateral notched (Fig. 1). The normal phenotype was considered the typical configuration with an allowance for only a minor notch at the level of the internal nasal valve and the nasal airway. The bilateral notched model has a prominent notch at the anterior vestibule in both the left and right nasal chambers. The unilateral notched model has a prominent notch in one chamber only, of the nasal cavity (in our models this is found in the left chamber of UN01 and the right chamber of UN02).

To capture more realistic airflow breathing entering the nasal cavity, a breathing region with dimension of 60 mm × 60 mm × 65 mm in front of each subject's face was created. To increase numerical stability and prevent reversed flow at the nasal pharynx outlet, an artificial extension pipe with a length of 50 mm (approximately 10 times of the pipe's diameter) was connected to the end of nasal pharynx of each model to allow fully developed outflow conditions. Steady flow condition with a flow rate of 15 L/min was imposed at outlet for all nasal models. A pressure-inlet condition with zero gauge pressure was used for all breathing zone facets. No-slip, stationary wall boundary condition was imposed on face and nasal cavity surfaces (Fig. 2).

It is worth noting that the modelling choice between steady [31–34] and unsteady [35–37] flow has already quite discussed in the literature. Human respiration statuses are cyclic and periodic with maximum and minimum flow rates, and most numerical airflow simulations using healthy nasal cavities under