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RHINOLOGY: NASAL OBSTRUCTION (JV NAYAK, SECTION EDITOR)

# Computational Fluid Dynamics (CFD) Modeling as an Objective Analytical Tool for Nasal/Upper Airway Breathing

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## Abstract

*Purpose of Review* Empty nose syndrome (ENS) is a rare yet debilitating disease that has been associated with aggressive removal of the inferior turbinate region in which patients report paradoxical symptoms of nasal obstruction and suffocation. The purpose of this review is to identify the mechanisms driving symptoms of ENS in patients to better alleviate them.

*Recent Findings* Recent studies have shown that patients with ENS have a characteristic "jet stream" of air that flows through the middle meatus when compared to healthy controls who have a dispersed pattern of airflow through all three meatae.

*Summary* Here, we found that the combination of altered nasal aerodynamics may contribute to a decrease in mucosal sensory function. This suggests that while ENS patients are inspiring comparable volumes of air compared to others, it is not being detected and communicated to the brain becoming interpreted as the symptoms of obstruction. Future research targeting how to improve sensory function by restoring airflow patterns should be considered to improve the efficacy of treatment for patients with ENS.

**Keywords** Empty nose syndrome · Computational fluid dynamics · Nasal airflow dynamics

## Introduction

Approximately 600 thousand ambulatory nasal sinus surgeries were performed annually in the USA [1]. The most common sinonasal surgeries among them are turbinate reduction and septoplasty or a combination of both. The outcomes of these surgeries are variable but generally good, with short-term favorable outcomes of about 60–90% [1–3]; however, rare complications have occurred. One of these complications is empty nose syndrome (ENS), and it is one of the most controversial and rare complications. Its incidence has been suggested to be related to aggressive removal of the inferior turbinate soft tissue [4, 5] with patients suffering from ENS often reporting debilitating symptoms of nasal obstruction, suffocation, nasal burning, nasal dryness, and nasal crusting [6], paradoxically after widening the caliber of the nasal passage via turbinate tissue removal. Due to the severity of these symptoms, ENS patients often struggle with psychosocial issues and can present with comorbid psychiatric problems such as anxiety and depression [7] that can significantly reduce the effectiveness of conventional treatment [8]. A recent approach to address these symptoms includes restoring the spatial contouring of the nasal cavity via submucosal implants. Furthermore, it has been seen that ENS patients are best diagnosed via the cotton test [9], which involves the blinded placement of a dry cotton plug into the site of greatest tissue loss and then evaluating patient ENS6Q symptom scores. These methods suggest that nasal airflow patterns and perception of airflow may be contributing factors toward perceived obstruction and ENS symptoms.

## Clinical Assessment

The only validated measure of objective patient reported symptoms that is ENS specific is the Empty Nose Syndrome 6-item Questionnaire (ENS6Q) [6]. In this questionnaire,

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patients rate their nasal symptoms from “0” (non-existent) to “5” (extremely severe) for the six different items: dryness, sense of diminished nasal airflow, suffocation, nose feels too open, nasal crusting, and nasal burning. A cut-off of 11 out of 30 was established to indicate that a patient has ENS. Another clinical test used to assess treatment viability for ENS is the cotton test. Here, a dry cotton plug is inserted into the region of greatest tissue loss within the nasal cavity. After a few minutes, the patients retake the ENS6Q, and the two scores (pre- and post- cotton) are compared. Often, patients with ENS will report significant improvements. Significant improvements after the cotton test usually result in a form of inferior meatus augmentation procedure (IMAP) in which a submucosal rib cartilage is implanted where the cotton plug optimized breathing [10•].

## Computational Fluid Dynamics

Often, experimental measurements of nasal airflow are impractical and limited by time constraints during clinical visits. In order to assess the differences in nasal aerodynamics and their impact on ENS symptoms, image-based computational fluid dynamics simulations were run. Here, patient-specific models are generated and run given various breathing conditions (Fig. 1A–C). The data generated from these models consists of various parameters such as flowrate through the nasal cavity, shear forces, and heat flux (index of nasal cooling). The data can be further analyzed spatially (inferior, middle, superior, anterior, etc.) within the nasal cavity to assess trends among different pathology groups. This data is then used to improve our understanding of the driving factors behind ENS.

Patient research CT scans were imported into AMIRA (Visualization Sciences Group, Hillsboro, OR, USA) software, and a 3-dimensional volume was created from 2-dimensional coronal, lateral, and axial images (Fig. 1A). The volume was created following image smoothing and artifact correction. It was then imported into a second commercial software package, ICEM CFD (Ansys, Inc., Canonsburg, PA, USA) where the volume was meshed, thus creating a polygonal representation of the interior volume of the nasal cavity so that computational analysis could be performed. This results in about 1.1 million to 3.6 million hybrid finite elements for each nasal cavity geometry (Fig. 1B).

Steady-state conditions were assumed, and the Navier–Stokes equations were solved with incompressible flow using ANSYS Fluent 16.2 (Ansys, Inc., Canonsburg, PA, USA). Other model assumptions include nasal wall rigidity and a no slip boundary condition on the walls. To simulate restful breathing, a state most relevant to patients’ symptoms during routine daily life [11, 12], a pressure drop of 15 Pa was applied between the nostrils and nasopharynx. The numerical solutions of the continuity and momentum equations were determined using the finite volume method. Continuous pressure and velocity fields were discretized using a second-order upwind scheme for numerical simulations and the SIMPLEC algorithm was used for pressure–velocity coupling. To ensure the methods represent in vivo phenomena, the numerical method applied in the current study has been validated by comparing with experimental measurements [13, 14].

## Menthol Lateralization Detection (LDT) Thresholds

Impaired nasal sensory function as a result of surgery has also been suggested to contribute to ENS symptoms. To assess subjects’ perceived nasal sensory sensitivity to airflow, the nasal trigeminal sensitivity can be measured through lateralization detection thresholds (LDTs) to menthol. The LDT is a measure of nasal trigeminal sensitivity independent of the chemical’s effect on the olfactory system, based on the fact that nonirritating odorants cannot be lateralized [21]. Menthol is used for its ability to activate the TRPM8 cool sensitivity pathway. Thus, impaired menthol LDT may indicate patients’ lack of ability to sense airflow

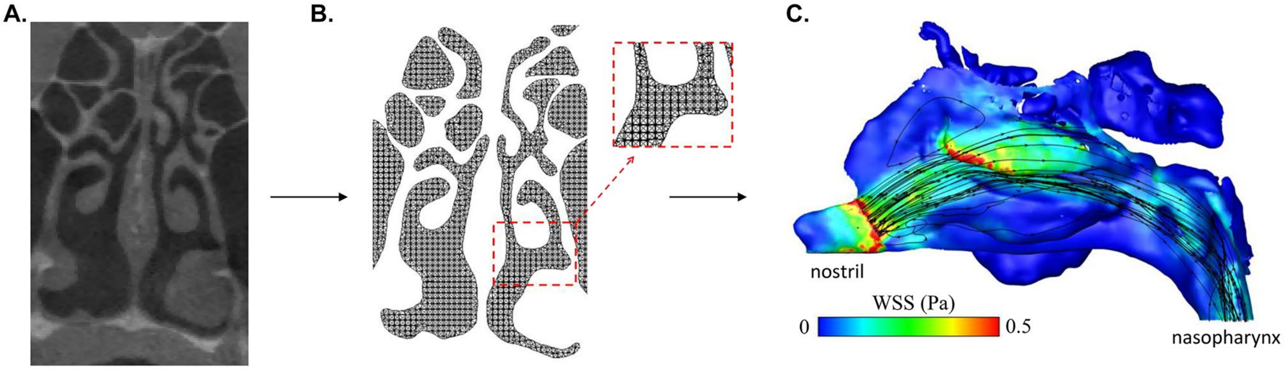

**Fig. 1** Patient-specific 3D models were generated using CT scans and run given various breathing conditions

cooling. The procedure used is consistent with reported literature methods [15, 16, 17•, 18] where menthol is diluted into mineral oil in a binary dilution series with 20 steps. Two bottles, one containing the target, menthol in a dilution step, and the other with only the solvent, mineral oil, were used in the trail and randomly inserted into each nostril via nose piece. The subject was instructed to sniff from both bottles and identify which one contained menthol. The trials were conducted based on a force choice ascending method of limits as previously described [19].

## Clinical Studies of Empty Nose Syndrome Patients

Empty nose syndrome is one of the most controversial and rare complications following sinonasal surgeries and is thought to be an iatrogenic phenomenon following possible over-resection of the inferior turbinate soft tissue [1, 2]. Paradoxically, patients often suffer from the perception of obstruction and suffocation despite having an obstruction free nasal cavity. However, very little is known about the forces that drive ENS symptoms and patient indicators that may lead to the complication.

Analysis nasal airflow distribution for patients who underwent aggressive ITR surgery shows that the individuals who developed ENS have significantly more airflow through the middle meatus when compared to the individuals who reported improvements [18]. In a study conducted by Malik et al. [20••] computational fluid dynamic models were created for six individuals during the cotton test. Here, a significant shift in airflow away from the middle meatus was observed (~40%) and redistributed throughout the nasal cavity (Fig. 2A). This shift correlated with a > 7-point shift in ENS6Q score, indicating that the distortion of nasal airflow due to a lack of spatial contouring within the nasal cavity could be contributing to patient symptoms. The study also highlighted the efficacy of using the cotton test to identify appropriate candidates for submucosal implants. Submucosal implants have been shown to restore the spatial contouring of the nasal cavity and improve both anatomical and psychological symptoms of ENS patients [21]. For example, the inferior meatus augmentation procedure (IMAP) via submucosal rib cartilage implants has significantly improved patient symptoms as indexed by ENS6Q scores [10•]. It is hypothesized that the implant (Fig. 2B) mimics the inferior turbinate, and instead of acting as an obstacle to impede airflow, it disperses flow by means of the Coandă effect. Again, this change in airflow is consistent with results seen from the cotton test as well as supports the findings that the jet stream of air characteristic to patients with ENS may be driving symptoms.

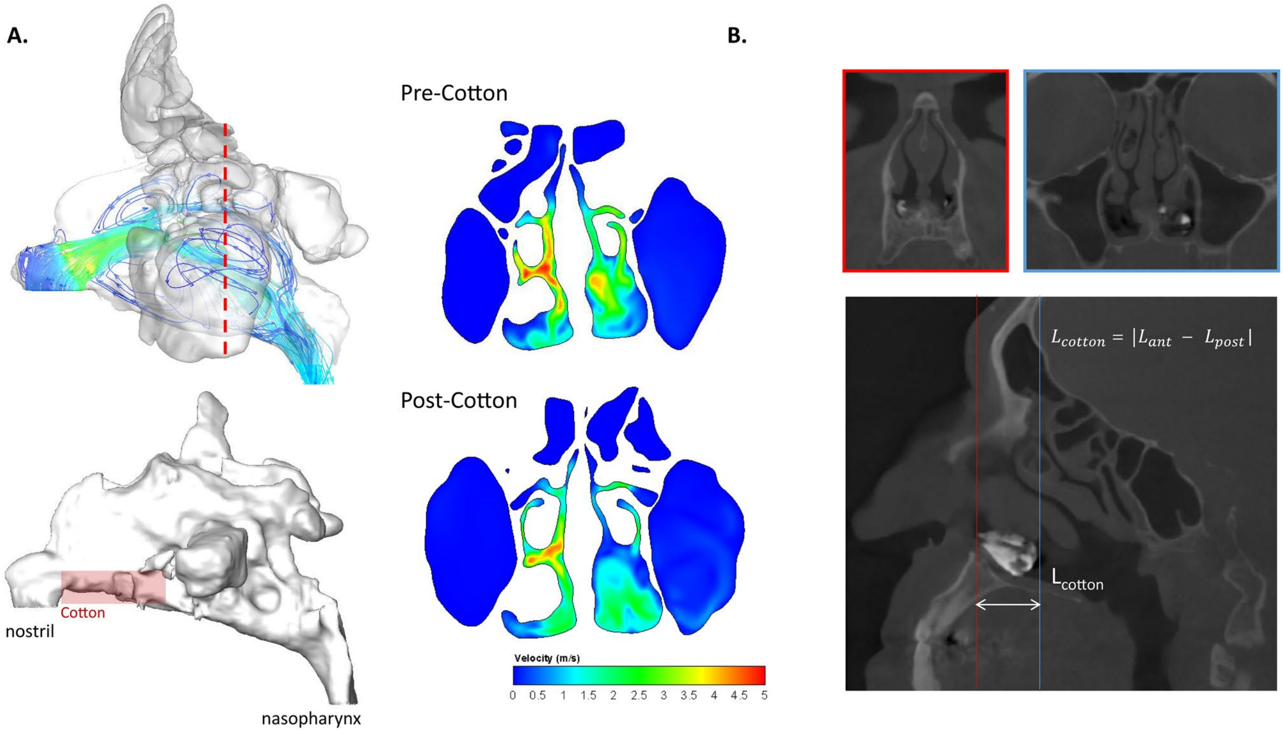

**Fig. 2** (**A**) significant shift in airflow away from the middle meatus was observed (~40%) and redistributed throughout the nasal cavity. (**B**) The implant mimics the inferior turbinate

Nasal neurosensory impairment due to wound healing or loss of sensory nerve fibers has also been thought to contribute to ENS. In a patient cohort of aggressive ITR surgery patients (both with and without ENS post-op), menthol LDT scores of the ENS patients are significantly lower (worse) than that of both healthy controls and the aggressive ITR group without ENS symptoms [18]. Since both aggressive ITR patient groups, in theory, experience the same scale of wound healing, the disruption of the mucosa trigeminal sensory function in ENS patients may be driving LDT scores and symptoms. One potential contributing cause could be that the perception of airflow requires the activation of nasal trigeminal cool receptors when cool ambient air is inspired [22, 23]. Thus, it is likely that the receptors are not being activated given the ENS jet stream through the middle meatus and the fact that less than 25% of the airflow is traveling through the inferior meatus. This would explain the low menthol LDT scores as the menthol may be unable to be successfully transported and activate the TRPM8 pathway.

## Concluding Remarks and Future Directions

The ability to understand the nasal aerodynamics of patients with ENS compared to other patient groups and healthy controls is critical in understanding the factors driving this rare condition. Through the use of patient-specific computational models and in vivo testing, we are able to better understand the mechanisms of ENS. Our data indicate that a combination of nasal aerodynamics potentially resulting in a decrease of mucosal sensory function potentially lead to ENS. In fact, when the spatial contours of the nasal cavity are restored either through the cotton test or surgical implants, ENS patients report significant improvement in symptoms. The findings indicate that CFD and menthol testing may be used as a potential objective diagnosis of ENS in the future and should be further explored.

The exact function of the inferior turbinate remains unknown; however, it appears to play a significant role is airflow distribution in the nasal cavity. Future CFD simulations to quantify the Coandă effects of the turbinate as well as characterize what drives changes in airflow should be explored. Hopefully, a better understanding of the mechanisms behind airflow distribution will optimize surgical outcomes and ultimately prevent ENS.

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## Declarations

**Conflict of Interest** The authors declare no competing interests.

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