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Impact of Middle vs. Inferior Total Turbinectomy on Nasal Aerodynamics

Anupriya Dayal, BS¹, John S. Rhee, MD, MPH², and Guilherme J. M. Garcia, PhD^{1,2}

¹Biotechnology and Bioengineering Center, Medical College of Wisconsin, Milwaukee, WI

²Department of Otolaryngology and Communication Sciences, Medical College of Wisconsin, Milwaukee, WI

Abstract

Objectives—This computational study aims to: (1) Use virtual surgery to theoretically investigate the maximum possible change in nasal aerodynamics after turbinate surgery; (2) Quantify the relative contributions of the middle and inferior turbinates to nasal resistance and air conditioning; (3) Quantify to what extent total turbinectomy impairs the nasal air conditioning capacity.

Study Design—Virtual surgery and computational fluid dynamics (CFD).

Setting—Academic tertiary medical center.

Subjects and Methods—Ten patients with inferior turbinate hypertrophy were studied. Three-dimensional models of their nasal anatomies were built based on pre-surgery computed tomography scans. Virtual surgery was applied to create models representing either total inferior turbinectomy (TIT) or total middle turbinectomy (TMT). Airflow, heat transfer, and humidity transport were simulated at a 15 L/min steady-state inhalation rate. The surface area stimulated by mucosal cooling was defined as the area where heat fluxes exceed 50 W/cm².

Results—In both virtual total turbinectomy models, nasal resistance decreased and airflow increased. However, the surface area where heat fluxes exceed 50 W/cm² either decreased (TIT) or did not change significantly (TMT), suggesting that total turbinectomy may reduce the stimulation of cold receptors by inspired air. Nasal heating and humidification efficiencies decreased significantly after both TIT and TMT. All changes were greater in the TIT models than in the TMT models.

Conclusion—TIT yields greater increases in nasal airflow, but also impairs the nasal air conditioning capacity to a greater extent than TMT. Radical resection of the turbinates may decrease the surface area stimulated by mucosal cooling.

Corresponding Author: Guilherme J.M. Garcia, PhD, Assistant Professor, Biotechnology & Bioengineering Center, Department of Otolaryngology and Communication Sciences, Medical College of Wisconsin, 8701 Watertown Plank Road, Milwaukee, WI 53226, Phone: 414-955-4466, Fax: 414-955-6568, ggarcia@mcw.edu.

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Keywords

middle turbinate resection; inferior turbinate reduction; nasal airway obstruction; computational fluid dynamics (CFD) simulations; secondary atrophic rhinitis; empty nose syndrome; mucosal cooling; nasal airflow sensation

Introduction

Partial middle turbinate resection (MTR) is commonly performed to improve the intraoperative view during functional endoscopic sinus surgery (FESS) and also as a treatment for nasal airway obstruction (NAO) in patients with concha bullosa. However, the physiologic consequences of MTR remain poorly understood. Over the years, otolaryngologists have debated about the benefits and risks of MTR. Proponents argue that MTR during FESS has many benefits, including ease of post-operative care, decreased synechia formation, and higher antrostomy patency rates. In contrast, middle turbinate preservationists argue that the middle turbinate plays important physiological roles in air conditioning, sinus ventilation, air filtration, and olfaction, and that its resection carries a risk of cerebral spinal fluid (CSF) leak.¹ Atrophic rhinitis and empty nose syndrome are feared complications of turbinate tissue resection, but they seem to be more often associated with total inferior turbinectomy than with partial MTR.^{1,2} LaMear and colleagues speculated that MTR carries a lesser risk of crusting and drying because the middle turbinate plays a relatively minor role in nasal air conditioning due its low density of erectile tissue and smaller surface area relative to the inferior turbinate.¹ This statement, however, remains speculative because objective studies quantifying the relative contributions of the middle and inferior turbinates to nasal air conditioning are lacking.

Previous research evaluating objective outcomes after turbinate surgery focused primarily on quantifying nasal resistance to airflow.^{3,4} This historical focus on nasal resistance is partly due to the availability of devices to measure nasal resistance in vivo (e.g., rhinomanometry) and to quantify nasal anatomy (e.g., acoustic rhinometry, medical imaging). However, at least since the 1980s, it has been known that the sensation of nasal patency is as related to mucosal cooling as to nasal resistance.⁵ This is illustrated by the fact that the majority of subjects report a sensation of improved nasal patency after inhalation of cold receptor stimulants, such as menthol, without any corresponding changes in nasal resistance.⁵ Therefore, it is desirable to develop a technique that can quantify the stimulation of cold receptors by inhaled air.

Computational fluid dynamics (CFD) simulations of nasal airflow have the ability to quantify heat exchange in 3-dimensional (3D) patient-specific models, thus providing objective measures of mucosal cooling. In addition, CFD simulations can be used to quantify moisture transport in the nasal cavity, and thus potentially shed some light on the pathophysiological processes responsible for nasal dryness and crust formation in empty nose syndrome patients.⁶ However, changes in nasal humidification efficiency after nasal surgery have rarely been investigated,⁶⁻⁸ with most computational studies to date focusing on nasal resistance⁹⁻¹³ and heat transfer.¹⁴⁻¹⁸ Importantly, the vast majority of previous

computational studies were aimed at inferior turbinate reduction,^{7,9-11,15} thus the aerodynamic changes after middle turbinate resection remain poorly understood.^{19,20}

Another advantage of CFD is the ability to perform virtual surgery and to compare the impact that different surgical techniques would have in the same patient, thus eliminating confounding factors inherent to in vivo studies where non-identical patients undergoing non-identical surgeries are compared. This paper aims to study the impact of total middle turbinectomy (TMT) versus total inferior turbinectomy (TIT) in nasal aerodynamics and air conditioning. We performed virtual surgery on the pre-operative computed tomography (CT) scans of 10 NAO patients to completely remove either the middle turbinate or the inferior turbinate. Complete resection of the turbinates, rather than partial resection, was selected as a method to investigate the theoretical maximal effect of turbinate removal on nasal aerodynamics and air conditioning. CFD simulations of inspiratory airflow were used to quantify nasal resistance, intranasal airflow distribution, nasal heating efficiency, nasal humidification efficiency, and the surface area stimulated by mucosal cooling as defined by Sullivan and colleagues.¹⁷

Methods

Patient Selection

The Institutional Review Board at the Medical College of Wisconsin approved this study with informed consent obtained from each patient. This manuscript is part of a larger study aimed at correlating objective and subjective measures of nasal patency.^{7,12,16-18,21} Twenty seven patients undergoing NAO surgery (septoplasty, inferior turbinate reduction, and/or rhinoplasty) have been recruited. Ten patients from this cohort were randomly selected for this study. Pre-surgery axial CT scans were obtained with 0.6 mm increments and a pixel size of 0.31 mm.

Creation of Pre-Surgical Models

Three-dimensional reconstructions of the nasal passages from pre-surgery CT scans were created Mimics 16.0 (Materialise, Inc.) using a range of -1,024 to -300 Hounsfield units. The nasal passage reconstructions extended from the nostrils to the nasopharynx, excluding the paranasal sinuses.

Creation of Virtual TIT and TMT Models

Virtual turbinectomy models were created based on the pre-surgery CT scans of all 10 NAO patients (n=10). For all patients, virtual TIT and TMT were performed along the entire length of the respective turbinate on the cavity contralateral to the patient's septal deviation, which is the side of compensatory IT hypertrophy. Although complete resection of the turbinate is rarely performed, we chose to study the most aggressive surgery possible as a theoretical limit of the maximum impact TIT or TMT can have on nasal aerodynamics.

For each patient, virtual TIT and TMT models were created by merging the original pre-surgical airspace to the volume occupied by the respective turbinate. In Mimics software, a "mask" is a group of voxels that users define using pixel thresholding and hand-editing. The

first step in constructing models was to create one mask representing the nasal airspace and another mask representing the IT or MT. The IT or MT mask was then added to the pre-surgery nasal airspace mask to create the virtual TIT and TMT models respectively (Figure 1).

Accounting for the 20 virtual surgery models (10 patients $\times$ 2 types of surgery), in addition to the 10 original pre-surgical models, a total of 30 different models were investigated.

CFD Simulations

Steady-state, laminar, inspiratory airflow simulations were conducted in Fluent 14.0 (ANSYS, Inc.) with the following boundary conditions: (1) inlet pressure at the nostrils = 0 Pa, (2) no slip at the walls, and (3) outlet pressure set to a value that resulted in a bilateral airflow rate of 15 L/min, which corresponds to an adult breathing at rest.⁷⁻¹³ The outlet pressure required to reach 15 L/min was obtained by running preliminary simulations and fitting the relationship between outlet pressure (P_{outlet}) and bilateral flowrate (Q) with a power law $P_{outlet} = aQ^b$, where a and b are constants. The boundary conditions for the heat transfer and water transport simulations were (1) $T=20^\circ\text{C}$ and $RH=50\%$ at the nostrils, and (2) $T=32.6^\circ\text{C}$ and $RH=100\%$ at the nasal mucosa, where T is the air temperature and RH is the relative humidity. The average mucosal temperature of 32.6°C during inspiration is based on experimental measurements by Lindemann and colleagues.¹⁴ To account for inter-individual variations in nasal anatomy, a relative distance from nostrils was defined as $D = Z/L_{septum}$, where Z is the distance from nostrils and L_{septum} is the septal length measured from the first coronal section after the nostrils ($Z = 0$) to the nasal choana. The nasal cavity was modeled as a rigid structure, which means that our methods do not account for wall compliance in patients with nasal valve collapse.

Biophysical Measures of Nasal Airflow

Nasal resistance ($R_{nose} = P/Q_v$) was defined as the ratio of the transnasal pressure drop P (nostrils to choanae) to the volumetric airflow rate Q_v . Since no anatomical changes were made to the contralateral side, all values reported in this manuscript refer to unilateral values on the virtually operated side. The surface area stimulated by mucosal cooling was defined as the surface area where heat flux exceeds 50 W/m^2 based on the analysis by Sullivan and colleagues.¹⁷

The assumption for all models was that the overlying mucosa was healthy and functioning in its normal capacity regardless of the final shape of the turbinate. Nasal humidification efficiency was defined as

$$\epsilon_{HUMIDIFICATION} = 100 \times \frac{C_{choana} - C_{nostril}}{C_{mucosa} - C_{nostril}}, \quad (2)$$

where $C_{nostril}$, C_{choana} , and C_{mucosa} are the water concentrations in air at the nostril, choana, and nasal mucosa, respectively. Similarly, nasal heating efficiency was defined as

$$\epsilon_{HEATING} = 100 \times \frac{T_{choana} - T_{nostril}}{T_{mucosa} - T_{nostril}}, \quad (3)$$

where $T_{nostril}$, T_{choana} , and T_{mucosa} are the air temperatures at the nostril, choana, and nasal mucosa, respectively. Choanal air temperature and water concentration were computed as mass-weighted averages at the posterior end of the septum, while our boundary conditions imply that $C_{nostril} = 0.00869 \text{ kg/m}^3$, $C_{mucosa} = 0.03694 \text{ kg/m}^3$, $T_{nostril} = 20^\circ\text{C}$, and $T_{mucosa} = 32.6^\circ\text{C}$.

Statistical Analysis

Two-tailed paired Students t-tests were used to test the hypothesis that virtual surgery resulted in statistically significant changes. Differences were considered significant for p-values < 0.05 .

Results

Complete resection of the nasal turbinates via virtual surgery significantly increased the nasal airspace. The average cross-sectional area in the turbinate region ($0.3 \leq D \leq 0.9$) increased from $1.1 \pm 0.1 \text{ cm}^2$ pre-surgery to $1.7 \pm 0.3 \text{ cm}^2$ after virtual TMT and to $2.6 \pm 0.3 \text{ cm}^2$ after virtual TIT (Figure 2). This increase in the nasal airspace was followed by a statistically significant reduction in nasal resistance. Unilateral nasal resistance in the virtually operated side decreased from an average of $0.23 \pm 0.21 \text{ Pa.s/ml}$ pre-surgery to $0.18 \pm 0.20 \text{ Pa.s/ml}$ after TMT ($p=0.0002$) and $0.08 \pm 0.03 \text{ Pa.s/ml}$ after TIT ($p=0.042$) (Figure 3A). The increase in nasal airspace resulted also in increases in nasal airflow. Unilateral airflow in the virtually operated side increased from $137 \pm 30 \text{ ml/s}$ pre-surgery to $153 \pm 28 \text{ ml/s}$ after TMT ($p=0.001$) and to $174 \pm 30 \text{ ml/s}$ after TIT ($p=0.0005$) (Figure 3B).

Airflow distribution within coronal cross-sections changed significantly after turbinate resection. To investigate this, a coronal cross-section at relative distance $D = 0.65$ was split into three regions: (1) inferior region (i.e., nasal floor, inferior meatus, and inferior septum), (2) middle region (i.e., middle meatus and middle septum), and (3) superior region (i.e., olfactory cleft and superior meatus) (Figure 4A). Unilateral airflow through the inferior, middle, and superior regions were respectively $39 \pm 10\%$, $53 \pm 9\%$, and $8 \pm 5\%$ of the total airflow pre-surgery. TMT increased the airflow allocation to the middle region to $75 \pm 7\%$, while reducing the airflow allocation to the inferior and superior regions to $19 \pm 7\%$ and $6 \pm 5\%$, respectively. Similarly, TIT increased airflow in the inferior region to $62 \pm 20\%$, while reducing airflow in the middle and superior regions to $36 \pm 18\%$ and $3 \pm 3\%$, respectively (Figure 4B, 4C).

Resection of the middle or inferior turbinates reduced the mucosa surface area available for heat and moisture exchange. On average, the surface area measured unilaterally from nostrils to the posterior end of the septum decreased from $97 \pm 14 \text{ cm}^2$ pre-surgery to $86 \pm 12 \text{ cm}^2$ after virtual TMT ($p<0.0001$) and $80 \pm 9 \text{ cm}^2$ after virtual TIT ($p<0.0001$). The greater reduction in nasal surface area after TIT as compared to TMT was statistically significant

($p=0.004$). Nasal heating efficiency and humidification efficiencies also decreased significantly after virtual TMT ($83\pm 8\%$ and $85\pm 7\%$) and after virtual TIT ($71\pm 6\%$ and $73\pm 6\%$) as compared to pre-surgery ($94\pm 6\%$ and $95\pm 5\%$) (Figure 5).

The surface area stimulated by mucosal cooling decreased from $49\pm 6\text{ cm}^2$ pre-surgery to $44\pm 4\text{ cm}^2$ after virtual TIT ($p=0.017$) (Figure 6). In contrast, TMT did not result in a statistically significant change in the surface area stimulated by mucosal cooling (46 ± 5 , $p=0.16$).

Discussion

Through computer simulations, we demonstrated that nasal resistance decreases and airflow increases after virtual total turbinectomy. Furthermore, our simulations reveal that nasal heating and humidification efficiencies are reduced from near 100% pre-surgery (which means that inspired air reaches mucosal temperature and full water saturation by the time it reaches the nasopharynx) to 60-80% after TIT. Nasal heating and humidification efficiencies decreased significantly after TMT as well, but the changes were more impressive in the TIT models.

The main functions of the nasal cavity, as universally mentioned in the rhinology literature, are olfaction, air filtration, and air conditioning (heating and humidification of inspired air). Impairment of the first two functions has clear health implications. Anosmia has a negative impact on a patient's quality of life, while a reduction in nasal filtration is associated with greater risk of lung diseases, as illustrated by a higher incidence of silicosis in miners with low nasal filtration compared to miners with high nasal filtration.²² In contrast, the health consequences of a reduction in the nasal air conditioning capacity are less obvious.

The incidence of respiratory tract infections peaks during winter,^{23,24} suggesting that exposure to cold temperatures and low air humidity reduces the immunity to airborne pathogens.²⁵ In addition, human evolutionists have found that the shape of the external nose correlates with climate, with human populations living in cold climates being more likely to have tall and narrow (leptorrhine) noses, while populations living in warm climates being more likely to have broad (platyrrhine) noses.^{26,27} These observations suggest that nasal air conditioning plays an important physiological role. However, when compared to other mammals, the nasal turbinates have a much simpler geometry in humans, which led some authors to conclude that the inferior turbinate of the human is a rather insignificant organ.^{1,28}

The physiological implications of a reduced nasal air conditioning capacity after total turbinectomy remain elusive. To date, most studies evaluating the effect of NAO surgery on nasal function focused on quantifying nasal resistance to airflow, with nasal air conditioning rarely being investigated. Some of the most feared complications of aggressive turbinate resection are secondary atrophic rhinitis and the empty nose syndrome, but the etiology of these diseases is not well understood.^{4,29,30} Nasal dryness and mucosal crusting are often observed in the enlarged nasal cavity of atrophic rhinitis patients,^{31,32} suggesting that an impaired air conditioning capacity plays a role in the pathophysiology.^{6,33} Ingelstedt and

Ivstam³⁴ measured the nasal humidification efficiency in healthy individuals and primary atrophic rhinitis patients by blowing dry air through one nostril and out through the other nostril while the soft palate was pressed passively against the posterior pharyngeal wall after local anesthesia. They reported that atrophic rhinitis patients with extensive crust formation had reduced nasal humidification efficiency as compared to healthy individuals. Similarly, Drettner and colleagues³⁵ reported a reduction in the nasal heating efficiency in 4 atrophic rhinitis patients as compared to 22 healthy individuals. However, it remains unclear whether this reduced nasal air conditioning capacity is an important factor in the pathophysiology or merely a downstream effect of a yet undetermined cause of atrophic rhinitis. Despite these uncertainties, it is clear that nasal airflow plays an essential role in the pathophysiology of atrophic rhinitis, given that symptoms disappear when nasal airflow is abolished by surgical closure of the nostrils to enforce mouth breathing.^{36,37}

Total turbinectomy is rarely performed in real life. It was studied here as a hypothetical example of an aggressive procedure that many otolaryngologists believe is linked to complications. In real life, partial turbinectomy is usually performed because it better preserves nasal function.³⁸ Although in theory partial turbinectomy also decreases the nasal heating and humidification efficiencies, it seems that the human nose can easily accommodate minor changes in nasal air conditioning. For example, Tsakirpoulou and colleagues measured intranasal air temperature and humidity in 57 NAO patients who underwent partial turbinectomy and reported a post-operative reduction of 13-16% in the nasal heating efficiency, but no change in the nasal humidification efficiency.³⁹ Importantly, they observed no major complications and no impact on clinical outcomes related to the air conditioning changes. Similarly, most patients undergoing radical turbinate resection do not develop atrophic rhinitis,⁴⁰⁻⁴² which suggests that a genetic⁴³ or environmental factor renders some patients less able to cope with a reduction in nasal air conditioning, and thus more susceptible to secondary atrophic rhinitis.

One of the most intriguing symptoms of atrophic rhinitis and empty nose syndrome is the sensation of nasal obstruction despite the enlarged nasal airspace. Moore and Kern⁴ reported that nasal resistance measured with rhinomanometry in a cohort of 135 patients with secondary atrophic rhinitis was 0.12 ± 0.03 Pa.s/ml, a value within the range for healthy subjects (0.15-0.30 Pa.s/ml). These in vivo measurements confirm the paradoxical nature of the symptom of nasal obstruction in these patients. However, evidence suggests that stimulation of TRPM8 cold receptors is as important as (if not more important than) respiratory effort for the perception of nasal airflow.^{5,44} Meusel and colleagues measured the respiratory epithelium response to menthol stimulation and found similar responses in various locations within the nasal cavity,⁴⁵ which suggests that menthol-sensitive TRPM8 cold receptors have a nearly uniform distribution within the nasal cavity. Recently, our group demonstrated that the surface area where heat flux exceeds 50 W/m^2 during inspiration correlated significantly with subjective nasal patency scores in a cohort of 10 NAO patients studied pre- and post-surgery, suggesting that sensation of nasal airflow is not limited to activation of cold receptors in one specific location, but may be the aggregate effect of cold receptor activation throughout the nasal cavity.¹⁷ Our simulations in the current study predicted that the surface area where heat fluxes exceed 50 W/m^2 decreased after TIT. These findings suggest a possible mechanism for the paradoxical sensation of nasal obstruction in

atrophic rhinitis and empty nose syndrome patients, namely complete resection of the turbinates may reduce the stimulation of cold receptors in the nasal mucosa, which may be interpreted as decreased airflow sensation.

To date, few computational studies have investigated the aerodynamic changes after middle turbinate resection. Di and colleagues used virtual surgery to perform either TIT or MTR in 7 healthy individuals.¹⁹ In agreement with our results, they reported a greater reduction in nasal resistance after TIT as compared to MTR. They also reported that airflow in the olfactory region decreased after TIT, but increased after MTR. Zhao and colleagues studied the aerodynamic changes in 1 NAO patient with concha bullosa who underwent MTR as a treatment for nasal obstruction.¹⁹ They reported that MTR resulted in negligible changes in the nasal airflow patterns, which were consistent with the persistent symptom of nasal obstruction reported by the patient post-operatively.

The main limitation of our study is its inherent computational nature and the lack of in vivo measurements to correlate with the predicted changes in airflow variables. CFD does not allow us to simulate post-operative healing, including mucociliary clearance and regrowth of nerves severed during surgery. Therefore, future studies should follow up patients undergoing radical turbinate resection to correlate clinical findings with changes in nasal aerodynamics. However, radical resection of the nasal turbinates is rarely performed and symptoms of empty nose syndrome and secondary atrophic rhinitis may take years to develop, thus making such studies challenging. Until the correlation of airflow variables and clinical findings is firmly established, our CFD simulations should be interpreted carefully.

In summary, our CFD simulations predict that radical resection of the inferior or middle turbinates leads to a reduction in nasal resistance, an increase in nasal airflow, and a reduction in the nasal air conditioning capacity, with TIT having a greater impact on nasal aerodynamics than TMT. Despite the increase in nasal airflow, the surface area where heat flux exceeds 50 W/m² decreased after TIT, thus suggesting that the stimulation of cold receptors may diminish after aggressive turbinate resection, potentially contributing to the paradoxical sensation of nasal obstruction reported by empty nose syndrome patients.

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Figure 1.

(A) Lateral view of the 3-dimensional pre-surgery model. (B) Outline of the pre-surgery (PRE), total inferior turbinectomy (TIT), and total middle turbinectomy (TMT) models overlaid on the pre-surgery CT scan.

Figure 2.

Average airspace cross-sectional areas as a function of distance from the nostrils in the pre-surgery (PRE), total middle turbinectomy (TMT), and total inferior turbinectomy (TIT) models.

Figure 3.

(A) Unilateral nasal resistance and (B) unilateral airflow in the virtually operated nasal cavity in the pre-surgery, TMT, and TIT models. Symbols denote statistically significant differences (* pre-surgery vs. total turbinectomy, § TMT vs. TIT).

Figure 4.

(A) 3D pre-surgery model. (B) Air velocity at coronal section D=0.65. (C) Airflow distribution among inferior, middle, and superior regions at D=0.65. Symbols denote statistical significance (* pre-surgery vs. total turbinectomy, § TMT vs. TIT).

Figure 5. (A) Nasal heating efficiency and (B) nasal humidification efficiency in the pre-surgery, TMT, and TIT models. Symbols denote statistically significant differences (* pre-surgery vs. total turbinectomy, § TMT vs. TIT).

Figure 6. Average surface area stimulated by mucosal cooling in the pre-surgery, total middle turbinectomy (TMT), and total inferior turbinectomy (TIT) models. Symbol denotes statistically significant differences (* pre-surgery vs. TIT).