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Identifying patients who may benefit from inferior turbinate reduction using computer simulations

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Abstract

Objectives—(1) To determine objective criteria to predict which patients may benefit most from inferior turbinate reduction surgery. (2) To test whether the site of turbinate reduction, either along the nasal floor (bottom resection) or along the septal side (medial resection), impacts the extent to which nasal resistance is reduced.

Study Design—Case series.

Methods—Three-dimensional reconstructions of the nasal anatomy of five nasal airway obstruction patients were created based on pre-surgical computed tomography scans. Inferior turbinate reduction models were created for each patient using virtual surgery. Airflow, heat transfer, and humidity transport during inspiration were simulated using computational fluid dynamics (CFD).

Results—Nasal resistance curves revealed little to no difference between bottom resection and medial resection models. In two patients, little change was observed in nasal resistance after virtual inferior turbinate reduction, which was attributed to the narrowest cross-sections being restricted to the anterior nose (i.e., anterior to the inferior turbinate). The three patients whose nasal resistances decreased substantially after virtual inferior turbinate reduction had a narrower airspace in the turbinate region and higher nasal resistance pre-surgery. Nasal air conditioning capacity was more affected by medial resections.

Conclusion—CFD simulations predicted no significant difference in the decrease in nasal resistance between virtual inferior turbinate reductions performed by bottom vs. medial resection of the turbinate. However, bottom resections better preserved the calculated humidification efficiency. The simulations predicted that the greatest reduction in nasal resistance occurs in patients with highest pre-surgical resistance in the turbinate region.

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Keywords

Nasal airway obstruction; nasal resistance; computational fluid dynamics (CFD) simulations; virtual surgery; inferior turbinectomy

INTRODUCTION

Chronic nasal airway obstruction (NAO) is an unpleasant condition characterized by subjective sensation of breathing difficulty, which is often caused by hypertrophy of the inferior turbinate (IT).¹ For patients whose symptoms persist after attempted medical therapy, surgical correction of the affected turbinate is often considered.^{2,3,4} However, no standard criteria are available to select which patients may benefit from IT reduction.^{5,6} In addition, no standard criteria are available to design the optimal anatomical shape of the turbinate as a target for surgery.

There are many techniques available to the surgeon to perform IT reduction, including partial or total turbinectomy, microdebrider-assisted inferior turbinoplasty, outfracture, submucosal resection, and radiofrequency-assisted turbinoplasty, among others.^{1,3} A number of these different techniques can be used interchangeably to arrive at a similar anatomical shape of the turbinate post-surgery. While numerous studies examined the effectiveness of the various techniques, there is a lack of studies assessing the post-surgery anatomical shapes with regards to nasal resistance. Using virtual surgery and computational fluid dynamics (CFD), one objective of this study is to determine whether either of two common resulting shapes of the IT (i.e., resection along the nasal floor or along the septal side) provides a greater reduction in nasal resistance.

In the absence of significant evidence to demonstrate that a specific shape of the IT results in optimal nasal airflow, surgeons typically perform the technique which they are most familiar with. This achieves the goal of reducing the IT size; however, the surgery's effectiveness (i.e., the extent to which nasal resistance is decreased) is often unclear. The objectives of this manuscript are to (1) determine objective criteria to predict which patients respond most effectively to IT reduction surgery, as measured by the extent to which nasal resistance decreases while preserving the nasal air conditioning function, and (2) test whether the site in which a turbinate reduction is performed, either along the bottom portion or along the medial portion of the IT, impacts the extent to which nasal resistance is reduced.

MATERIALS AND METHODS

Patient selection

This study was approved by the IRB committee at the Medical College of Wisconsin and informed consent was obtained from each patient. This manuscript is part of a larger study aimed at correlating objective and subjective measures of nasal patency in surgical NAO patients.⁷⁻¹⁰ Ten patients in this cohort had clinical indications for turbinate reduction surgery in conjunction with other functional nasal airway surgery such as septoplasty or septorhinoplasty. Due to the labor-intensive nature of developing 6 different virtual surgery

models per patient (see below), a subgroup of 5 patients was randomly selected for analysis. Pre-surgery axial CT scans were obtained with 0.6 mm increments and a pixel size of 0.313 mm.

Creation of pre-surgical models

Three-dimensional reconstructions of the pre-surgery nasal passages were created in the medical imaging software Mimics 16.0 (Materialise, Leuven, Belgium) using a range of −1,024 to −300 Hounsfield units. The reconstructions extended from the nostrils to the nasopharynx, excluding the paranasal sinuses.

Creation of virtual IT reduction models

Virtual IT reduction models were created based on the pre-surgery CT scans of all 5 NAO patients (n=5). For all patients, virtual IT reduction was performed along the entire length of the IT on the cavity contralateral to the patient's septal deviation, which is the side of compensatory IT hypertrophy. A series of different models were created representing various levels of resections performed along the bottom portion of the IT (i.e., along the nasal floor) or along the medial portion of the IT (i.e., along the septum). These two interventions were selected to represent common outcomes of IT surgery, and also as a method to systematically investigate how the IT shape affects nasal aerodynamics.

For each patient, virtual IT reduction models were created by merging the original pre-surgical airspace to the additional airspace generated by IT resection. In Mimics software, a "mask" is a group of voxels that users define using pixel thresholding and hand-editing. The first step in constructing bottom resection models was to create one mask representing the nasal airspace and another representing the IT (Figure 1). The second step was to create a copy of the IT mask and trim a selected number of pixels from the bottom portion of the IT along the entire axial length (i.e., full length turbinectomy). Three separate bottom resection models were created per patient, representing IT reductions of various extents (i.e., less aggressive to more aggressive). The resected IT masks for each model were then subtracted from the pre-surgery IT mask to obtain masks representing only the resected portions of the IT. These bottom resection layers were added to the pre-surgery nasal airspace mask to create the bottom resection models (Figure 1).

Three medial resection models were created per patient, representing resections performed to various extents. To construct the medial resection models, the first step was to dilate the pre-surgical airspace mask by a selected number of pixels (Figure 1). The dilated airspace mask was intersected with the IT mask to isolate the pixels around the IT. The resulting pixel layer was manually edited to further isolate the pixels along the medial portion of the IT. These medial resection layers were added to the pre-surgery nasal airspace mask to create the medial resection models (Figure 1).

To quantify the increase in nasal airspace after virtual surgery, the soft tissue volume resected by virtual surgery was calculated as $\Delta V_{IT} = V_{IT}^{PRE} - V_{IT}^{POST}$, where V_{IT}^{PRE} and V_{IT}^{POST} are the pre-surgery and post-surgery volumes of the IT masks, respectively, and V_{IT} is the surgical reduction in IT volume. To standardize the comparison between medial

resection and bottom resection models, the most aggressive virtual surgeries reduced the IT volume by similar amounts (1,000 to 2,000 mm³) in both types of models and in all patients. Accounting for the 30 virtual surgery models (5 patients × 2 types of surgery × 3 models/surgery), in addition to the 5 original pre-surgical models, a total of 35 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 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 is based on the experimental measurements by Lindemann and colleagues.¹⁴ 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.

Measuring anatomical characteristics as a function of distance from nostrils

The following method was used to identify the location of constrictions in the nasal passages. First, one streamline representative of the flow patterns was selected for each nasal cavity and each patient (Supplementary Figure 1). Second, cross-sections perpendicular to the streamline were created and the cross-sectional area plotted as a function of distance from the nostril. Finally, area-weighted average pressure was computed at sections 0, 2, 4, 6, and 8 cm from the nostrils (Supplementary Figure 1), thus allowing the quantification of pressure drops across each 2-cm segment and the identification of the most resistive segment of the nose.

Humidification efficiency and heating efficiency in the nasal cavity

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

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

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

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

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 $T_{mucosa} = 32.6^\circ\text{C}$.

RESULTS

Changes in nasal resistance for bottom vs. medial resection models

For all simulations, the nasal resistance curves revealed little to no difference between the bottom resection and the medial resection models (Figure 2). Virtual IT reduction resulted in little change in nasal resistance for patients 1 and 2 (reductions of 6% and 21%, respectively, for the maximally aggressive resection models). Virtual IT reduction for patients 3, 4, and 5 resulted in more favorable decreases in nasal resistance. For these patients, the greater the reduction in IT volume, the greater was the decrease in nasal resistance. The maximally aggressive resection models resulted in decreases in unilateral nasal resistance of 75%, 41%, and 58%, respectively, for patients 3, 4, and 5. Interestingly, the nasal geometries with the greatest reduction in nasal resistance were those with the highest pre-surgical unilateral nasal resistance (0.791, 0.218, and 0.249 Pa.s/ml in patients 3, 4, and 5 vs. 0.095 and 0.132 Pa.s/ml in patients 1 and 2, respectively, measured at $Q_V = 15 \text{ L/min}$).

Effectiveness of inferior turbinate reduction

To understand why the simulations for only three patients resulted in significant decreases in nasal resistance after virtual IT reduction, the cross-sectional areas and pressure drops along the nasal cavity were examined in the pre-surgery models (Figure 3). Patients 1 and 2 had clearly defined constrictions in the anterior region of the nasal cavity (0 to 2 cm from nostrils), and thus most of the pressure drop occurred in the anterior nose in these patients, i.e., the restriction was due to non-turbinate factors anterior to the location of the turbinate. Patients 3 and 5 had a narrower posterior nose with cross-sectional areas in the turbinate region (2 to 8 cm from nostrils) as small as or smaller than the cross-sectional areas in the anterior nose. Patient 4 had a prominent anterior constriction that extended beyond 2 cm from the nostril, combined with another narrowing 5–6 cm from the nostril. The data for patient 3 showed most of the pressure drop occurring 6 to 8 cm from the nostrils. In patients 4 and 5, there was a more gradual pressure drop throughout the turbinate region (Figure 3).

Impact on nasal air conditioning

Heating and humidification simulations were employed to examine the effect of virtual IT reduction on nasal air conditioning capacity, a physiologically important nasal function. IT reduction diminished the nasal heating and humidification efficiencies (Supplementary Figures 2 and 3). Medial resection models for patients 1, 2, 4, and 5 resulted in greater reductions in air conditioning efficiency than the bottom resection models. The only exceptions were the simulations for patient 3. Unlike other patients, virtual IT reduction in patient 3 effectively increased the nasal surface area available for humidity and heat transfer by dissociating the IT from the nasal septum. This increase in nasal surface area was greater for medial resections, and consequently, medial resections preserved the nasal air conditioning capacity more than bottom resections in this patient.

DISCUSSION

Surgical IT reduction is widely performed as a treatment for IT hypertrophy unresponsive to medical therapy.^{2,4} Many patients, however, continue to report persistent symptoms post-operatively.^{15,16} Several studies have investigated surgical outcomes using patient-reported subjective scales or objective measures of airflow,^{16–18} but few studies have quantified the post-surgery IT morphology and its relationship to clinical outcomes.¹⁹ Hanna and colleagues²⁰ reported that lateral outfracture of the IT resulted in inconsistent morphological changes affecting the IT shape, size, and position. Larrabee and Kacker³ reviewed level 1 evidence studies (prospective, randomized trials) and concluded that, due to the lack of randomized trials comparing multiple surgical techniques, no surgical technique can be decisively selected as the best at reducing symptoms of nasal obstruction. While various surgical techniques may result in a similar morphological shape, some procedures may cause mucosal injury, resulting in impaired nasal function.³ Therefore, recent studies have focused on mucosa-preservation techniques,⁴ aimed at preserving mucociliary clearance and the nasal air conditioning function.^{19,21}

Our computer simulations suggest that the location of IT reduction within a given cross-section (bottom resection vs. medial resection) is not a major determinant of the post-surgical decrease in nasal resistance. The most important factor seems to be the location where the nasal cavity is constricted, which may explain why certain nasal anatomies responded more favorably to virtual surgery than others. Haight and Cole²² found that the most resistive segment of the nasal cavity, known as the nasal valve, is normally confined to a short segment of a few millimeters situated at the junction of the compliant cartilaginous vestibule with the rigid bony cavum. In their study, approximately one-third and two-thirds of the nasal resistance were found in the cartilaginous vestibule and nasal valve region, respectively, while the turbinate region posterior to the nasal valve had an insignificant contribution. This is consistent with our results for patients 1 and 2, who experienced the majority of their pressure drop within the first two centimeters of the nasal cavity. Consequently, virtual IT reduction had a minimal effect on nasal resistance in these patients because it did not address their main site of obstruction. In the clinical setting, these patients had additional septal surgery to address these areas of constriction.

The nasal resistances of patients 3, 4, and 5, all of whom had significant pre-surgical resistance beyond the anterior two centimeters of the nasal cavity, were lowered substantially after virtual IT reduction. Accordingly, our data suggests that the patients most likely to have a significant reduction in nasal resistance after IT surgery are those who have substantial resistance in the turbinate region pre-surgery. Among the models created for each patient, the greater the volume of tissue removed, the greater was the decrease in nasal resistance.

While there was virtually no difference between the medial vs. bottom resection models with regards to the decrease in nasal resistance, nasal air conditioning was better preserved by bottom resection of the IT in most simulations. However, the clinical relevance of these differences in nasal humidification efficiency is unclear. Aggressive IT resection has been proposed to increase the risk of secondary atrophic rhinitis,^{23,24} but this remains

controversial.^{25,26} *In vivo* experiments have shown that, while the nasal cavities of healthy individuals humidify inhaled air to 90% relative humidity, atrophic rhinitis patients with extensive crust formation achieve only 60% relative humidity.²⁷ However, whether nasal dryness is a cause or a symptom of atrophic rhinitis is a matter of debate.^{12,24,25} It is conceivable that our most aggressive virtual IT reductions, which reduced nasal humidification efficiency to 77% in some models, may have reached a limit where aggressive IT reduction could have physiological implications. Future studies are required to determine the minimal value of nasal humidification efficiency that is acceptable after IT surgery.

One limitation of our study is that turbinate reduction was considered in isolation without modeling septoplasty. In reality, these two procedures are often performed together. By displacing the septum towards the midline, septoplasty decreases the airspace in the cavity where the IT is hypertrophied. Therefore, although our simulations predicted that IT reduction alone would have a minor effect on unilateral nasal resistance in patients 1 and 2, it is possible that IT reduction would be beneficial in conjunction with septoplasty in these patients. Another limitation is that this theoretical study did not include *in vivo* measurements to validate to what extent our computational predictions correlate with actual surgical outcomes in real patients.

Several groups have used CFD simulations to investigate the aerodynamic consequences of virtual IT reduction. Wexler and colleagues²⁸ were the first to apply CFD technology to investigate airflow patterns after IT reduction; they reported that partial inferior turbinectomy resulted in significant reductions in the transnasal pressure drop in one individual. Lee and colleagues²⁹ used medical imaging software to artificially expand the inferior turbinate of a healthy volunteer and thus create a severely obstructed nose model. Subsequently, virtual surgery was performed to compare the aerodynamic effects of three IT reduction procedures, namely anterior resection, full-length resection of one-third of the IT height, and total turbinectomy.²⁹ They concluded that the full-length one-third resection resulted in the greatest decrease in nasal resistance. Chen and colleagues³⁰ utilized CFD simulations to evaluate the impact of IT reduction on nasal heating efficiency. They reported that excessive partial or total turbinate resection impairs the nasal heating function. Our study contributes to this growing literature by demonstrating that CFD simulations can be used to identify nasal anatomies in which the nasal resistance is most likely to be significantly lowered after IT reduction.

CONCLUSION

CFD has emerged as a powerful tool to examine the aerodynamic effects of nasal surgery. Our computer simulations and virtual surgery modeling suggest that (1) there is no significant difference in the decrease in nasal resistance between an IT reduction performed by bottom resection vs. medial resection of the IT, and (2) the patients most likely to benefit from IT reduction are those with the greatest pre-surgical resistance in the turbinate region.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Method to perform virtual turbinate reduction surgery. (TOP) The inferior turbinate (IT) was isolated within the nasal cavity and trimmed along the bottom portion by a selected number of pixels to create each of three IT resection models. The resection layer was then united with the pre-surgery nasal airspace to create the bottom resection models. (BOTTOM) The pre-surgery airspace was dilated by a selected number of pixels, and the layer of pixels along the medial portion of the IT was isolated. The medial resection layer was united with the pre-surgery airspace to create the medial resection models. (BOTH) Three-dimensional models are represented by the outlines in the panels on the far right. Note that the pre-surgery model outlines are included for reference.

Figure 2.

Unilateral nasal resistance as a function of the reduction in inferior turbinate (IT) volume in the pre-surgery, bottom resection, and medial resection models. Note that patients 1 and 2 experienced minor decreases in nasal resistance after virtual IT reduction, while patients 3, 4, and 5 experienced more significant decreases.

Figure 3.

Cross-sectional area (CSA) and pressure drop as functions of distance along the nasal passage in the pre-surgery models of patients 1–5. All values are unilateral in the side where inferior turbinate reduction was performed.