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A Hierarchical Stepwise Approach to Evaluate Nasal Patency after Virtual Surgery for Nasal Airway Obstruction

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Abstract

Background: Despite advances in medicine and expenditures associated in treatment of nasal airway obstruction, 25–50% of patients undergoing nasal surgeries complain of persistent obstructive symptoms. Our objective is to develop a “stepwise virtual surgery” method that optimizes surgical outcomes for treatment of nasal airway obstruction.

Methods: Pre-surgery radiographic images of two subjects with nasal airway obstruction were imported into Mimics imaging software package for three-dimension reconstruction of the airway. A hierarchical stepwise approach was used to create seven virtual surgery nasal models comprising individual (inferior turbinectomy or septoplasty) procedures and combined inferior turbinectomy and septoplasty procedures via digital modifications of each subject’s pre-surgery nasal model. To evaluate the effects of these procedures on nasal patency, computational fluid dynamics modeling was used to perform steady-state laminar inspiratory airflow and heat transfer simulations in every model, at resting breathing. Airflow-related variables were calculated for virtual surgery models and compared with dataset containing results of healthy subjects with no symptoms of nasal obstruction.

Findings: For Subject 1, nasal models with virtual septoplasty only and virtual septoplasty plus inferior turbinectomy on less obstructed side were within the healthy reference thresholds on both

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CONFLICT OF INTEREST STATEMENT

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sides of the nasal cavity and across all three computed variables. For Subject 2, virtual septoplasty plus inferior turbinectomy on less obstructed side model produced the best result.

Interpretation: The hierarchical stepwise approach implemented in this preliminary report demonstrates computational fluid dynamics modeling ability to evaluate the efficiency of different surgical procedures for nasal obstruction in restoring nasal patency to normative level.

Keywords

stepwise virtual surgery; nasal airway obstruction; computational fluid dynamics (CFD) simulations; normative thresholds; 3D nasal models

INTRODUCTION

Nasal airway obstruction (NAO) is a common health problem affecting all age groups, with a measurable negative effect on quality of life.^(1, 2) Annual costs associated with medications for managing NAO are estimated to be in excess of \$5 billion, and surgical intervention costs are estimated at another \$60 million,⁽³⁾ yet many patients do not find adequate relief from these treatments. Failure rates for NAO surgery are reported to be between 25% and 50% when considering complete resolution of patient symptoms.^(4–8) This implies that for the more than 340,000 people in the US that will have surgery to correct NAO this year,⁽⁹⁾ there could be as many as 170,000 failed surgeries this year alone. This high failure rate has been attributed to the fact that there is no “gold standard” to diagnose the extent and etiology of NAO, and no available tools to aid surgeons in predicting surgical success accurately.

The complexity and pathophysiology of NAO could be better understood using contemporary computational tools to describe functional changes in the airway. Computational fluid dynamics (CFD) is a well-established, powerful tool that can be used to model and analyze the dynamical aspects of nasal airflow. Previous research by our group has shown that certain CFD derived airflow-related variables correlate with patients' symptoms and quality of life (QOL) questionnaires pre-operatively and post-operatively,⁽¹⁰⁾ and that CFD virtual surgery simulation can predict *in vivo* surgery results.^(11, 12) CFD modeling research could produce a standard for pre-operative planning and assessment of nasal airway surgery through virtual surgery techniques. A number of studies have utilized virtual surgery techniques to investigate the influence of (inferior and/or middle) turbinectomy with/without septoplasty on airway patency.^(13–22) Some of these studies also examined how location and/or extent of turbinate resection enhance nasal patency after surgery.^(14–18) In contrast to turbinectomy, fewer virtual surgery studies have performed septoplasty.^(19–23) These studies highlight the ability of CFD modeling as an emerging pre-operative planning tool for assessing nasal airway surgery, aimed at optimizing surgical outcomes.

Nonetheless, before such a virtual surgery tool (i.e., user-friendly software development) for NAO can be used in a clinical setting, key methodological components of relevant surgeries need to be further developed. The two anatomic structures that are most commonly altered during surgery are the septum and inferior turbinate(s), as they are major contributors to symptoms of NAO. When deformed and/or hypertrophied, they account for abnormally high

levels of nasal resistance.^(11, 12) Part of routine surgical planning is deciding which structures should be altered surgically to provide the most relief from symptoms. On one hand, extensive surgery that involves all these anatomic structures would result in a wider nasal cavity, which theoretically would provide the greatest relief but may disrupt other nasal functions (air heating, humidification, and filtration); while minimally-invasive surgery may not completely relieve symptoms. This tradeoff between more surgery with potentially more benefits to patients, or less surgery with lower costs, lower risks and lower benefits, motivates the development of a computational tool for surgical planning that can improve patients' quality of life.

The next step towards making virtual surgery planning a reality is to develop methods for evaluating individual and combined septoplasty and inferior turbinectomy procedures, aimed at maximizing patient benefits and minimizing risk. To this end, the goal of the present study was to develop a "stepwise virtual surgery" approach to support a more effective method of surgical planning. Specifically, from patient-specific radiographic images of two NAO subjects, we created seven virtual surgery three-dimensional (3D) nasal models for each subject. Virtual surgery models were systematically created to reflect hierarchical combinations of septoplasty and inferior turbinectomy performed by surgeons for treatment of NAO. Next, a CFD modeling approach was implemented to quantitatively characterize the effects of septoplasty and inferior turbinectomy on nasal airflow-related variables, as well as describe how these airflow-related values from each surgical combination compares with those computed for healthy nasal function. The virtual surgery methods presented here are proof of concept highlighting the potential computational methods in identifying the best procedure that optimizes surgical outcomes from among the most commonly performed NAO surgeries. The concepts in the present report will be extended to a larger cohort of subjects in our subsequent work. To our knowledge, this is the first study to apply virtual surgery to investigate how combinations of septoplasty and inferior turbinectomy affect CFD-derived measures of nasal patency.

METHODS

The Institutional Review Board committee at Medical College of Wisconsin approved the research described here. Two subjects with a clinical diagnosis of non-reversible, surgically treatable cause for nasal obstruction were selected for this study. These subjects were chosen because their respective conditions represent relatively significant NAO, requiring aggressive septoplasty techniques that will benefit from performing a systematic "stepwise virtual surgery" approach to determine optimal surgical outcomes based on CFD-derived measures of nasal patency. The pre- and post-surgery computational nasal models of these two subjects were part of a cohort of 10 NAO subjects previously investigated by our group. (22, 24, 25)

Subject 1 is a 27-year-old, 72.6-kg, female with complaints of mainly right sided nasal obstruction. Her examination revealed significant rightward mid-septal deviation with displacement of the caudal end off of the maxillary crest to the left side and compensatory left inferior turbinate hypertrophy. The patient underwent an open rhinoplasty approach consisting of transposition of the displaced caudal septum and placement of a left spreader

graft to help straighten the deviated dorsal septum. The patient also underwent left inferior turbinate reduction via submucosal resection. The patient had an uneventful post-operative course. Subject 2 is a 22-year-old, 52.0-kg, female with complaints of mainly left sided nasal obstruction. Her examination revealed significant leftward septal deviation. The patient underwent an open rhinoplasty approach for an aggressive septoplasty with essentially replacement of the L-strut of the septum. This patient also exhibited an uneventful post-operative course.

Virtual Surgery Methods

A hierarchical approach to determining effects of septoplasty and inferior turbinectomy on CFD variables was undertaken virtually using a stepwise approach, creating 7 3D nasal models described in Table 1 per subject. These 3D nasal models comprised *individual* (turbinectomy or septoplasty) procedures and *combined* turbinectomy and septoplasty procedures (Fig. 1). For each respective stepwise virtual surgery procedure, turbinectomy and/or septoplasty were reconstructed from subject-specific pre-surgery computed tomographic (CT) scans imported into the medical imaging software package, Mimics™ 13.1 (Materialise, Inc., Leuven, Belgium). In addition to the creation of these virtual models, both subjects' pre- and post-surgery 3D nasal models were reconstructed from their pre- and post-surgery CT images (pixel size of each CT was 0.31 mm × 0.31 mm).

The creation of virtual inferior turbinectomy involved systematic removal of 0.62 mm (corresponding to 2-pixel reduction) along the entire length of the inferior turbinate in the pre-surgery radiographic images in Mimics™ (Fig. 1). This process virtually reduces the inferior turbinate thickness, thus mimicking actual full-length inferior turbinectomy performed by surgeons. The 3D virtual septoplasty reconstruction reflected anatomical changes expected to arise from each subject's actual septoplasty (Fig. 1). The *individual* virtual procedures consisted of [1] inferior turbinectomy on predominately obstructed side (OIT); [2] inferior turbinectomy on less obstructed side (UIT); and [3] septoplasty (SEP). In addition, virtual surgery models involving the *combination* of inferior turbinectomy and septoplasty were [1] bilateral inferior turbinectomy (BIT); [2] septoplasty and inferior turbinectomy on predominately obstructed side (SEP-OIT); [3] septoplasty and inferior turbinectomy on less obstructed side (SEP-UIT); and [4] septoplasty and bilateral inferior turbinectomy (SEP-BIT).

Another aspect of routine surgical planning for NAO is deciding how much (complexity) surgery to perform based on patient's clinical assessment and diagnosis. "Complexity" of surgery can be difficult to define, as it may have qualitative and quantitative components. For nasal airway surgery (specifically septoplasty and inferior turbinectomy), the operative time needed for the procedures or increased risk of complications can arguably be a quantifiable surrogate outcome measure for "complexity" - i.e. less complex surgery translates to less surgery which amounts to shorter surgical time and less patient morbidity/healing time. In addition, most surgeons would likely agree that turbinate surgery is less complex than septoplasty further adding to the face validity of our virtual surgery models reflecting the different surgical procedures. As noted in Table 1, the standard operative time needed to perform each of the 7 procedures was assigned a complexity ranking. Therefore,

the different “stepwise virtual surgery” scenarios were ranked from least complex as 1 (unilateral inferior turbinectomy) to most complex as 5 (septoplasty with bilateral inferior turbinectomy).

Airflow Simulations:

To solve the discretized governing equations of fluid flow, all 3D nasal models were imported into the mesh-generation software package ICEM-CFD™ 16.1 (ANSYS, Canonsburg, PA) for construction of planar inlet surfaces around the nostrils and an outlet surface at the end of a 2cm tube attached to the nasopharynx. Next, discretization of each 3D nasal airspace fluid domain was done by creating approximately 4 million graded unstructured tetrahedral elements. In addition, mesh quality analysis was done to ensure that tetrahedral elements aspect ratio was adequately smoothed to prevent distorted elements from affecting the accuracy of our numerical simulations. Approximately 4 million tetrahedral mesh elements were chosen based on a prior mesh sensitivity analysis study reported in Frank-Ito et al. ⁽²⁶⁾ showing that about 4 million elements provide mesh independent numerical results.

Following discretization of nasal models, the CFD software package Fluent™ 16.1 (ANSYS, Inc., Canonsburg, PA) was used to conduct steady-state simulations of laminar incompressible inspiratory airflow and heat transfer at resting inhalation rates. ANSYS Fluent™ uses the finite volume method in cell-centered approach to numerically solve the discretized Navier-Stokes equations. Since the flow velocities through the nasal passage during low to moderate breathing rate usually have a Mach number $\ll 0.2$,⁽²⁷⁾ the conservation of mass and momentum governing equations for laminar, incompressible steady state flow reduces to

$$\nabla \cdot \vec{u} = 0,$$

(1)

$$\rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu \nabla^2 \vec{u},$$

(2)

where $\vec{u} = \vec{u}(x, y, z)$ is the velocity vector, $\rho = 1.204 \text{ kg/m}^3$ is fluid density, $\mu = 1.825 \times 10^{-5} \text{ kg/m-s}$ is dynamic viscosity, and p is pressure. The thermal energy equation for heat transfer is defined as

$$\rho c_p (\vec{u} \cdot \nabla) T = k \nabla^2 T,$$

(3)

where $T = T(x, y, z)$ is temperature, $k = 0.0268$ W/m-K is thermal conductivity, $c_p = 1005.9$ J/kg-K is specific heat of air. Since the physical properties of air were assumed constant, airflow and heat transport were considered decoupled.

Pressure boundary conditions were used to drive airflow at resting breathing in each subject. A target flow rate was set equal to twice each subject's estimated minute volume (amount of air exhaled in 1 minute) based on gender-specific power law curves suggested in Garcia et al. (28) As these curves were derived for healthy individuals, an overall pressure drop from nostrils to outlet that produced airflow approximating each subject's target flow rate was determined in the healthier, post-surgery nasal model reported in prior publications by our group. (24, 25) An overall pressure drop from nostrils to outlet for the pre-surgery model and all 7 "stepwise virtual surgery" models was then imposed so that pressure drop from nostrils to choana in these models were consistent with those attained for their respective post-surgery models (Table 2). (24, 25) This method avoided confounding effects on flow rates and pressure drops caused by dynamic differences in pre- and post-surgery nasopharyngeal size. (29) Additional boundary conditions specified in these simulations were [1] at the nasal wall, no-slip, stationary wall, temperature was set at 32.6°C; [2] at the nostril inlet, a "pressure-inlet" boundary condition was specified at the inlet surface with gauge pressure set to zero, and temperature at 20°C; and [3] a "pressure-outlet" condition at the outlet with temperature set to 32.6 °C and a negative gauge pressure set to target same pressure drop from nostrils to choana.

Computed Variables to Report:

Analyses conducted from previous studies by our group suggest that the following CFD computed airflow-related variables have the best correlations with patient-reported quality of life assessments: [1] unilateral airflow rate; [2] unilateral flow as a fraction of bilateral flow (airflow partition); [3] unilateral heat flux (HF); [4] unilateral nasal resistance as a fraction of bilateral nasal resistance (nasal resistance ratio); and [5] unilateral mucosal surface area where HF exceeds 50 W/m² (SAHF50). (24, 25) Since computed variables [2] and [4] are inversely related and variable [3] and [5] both contain information about HF, analysis in the present study focused on results pertaining to unilateral airflow rate ([1]), airflow partition ([2]), and unilateral SAHF50 ([5]). Additional rationale underlying our decision to focus the analysis on these three computed variables is that they generated the strongest correlations ($r = -0.70$ for [1]; $r = -0.71$ for [2]; and $r = -0.76$ for [5]) with patient-reported survey. (24, 25) Computed variables from pre- and post-surgery and 7 "stepwise virtual surgery" models for each subject were compared with recently obtained (soon to be published) normative ranges dataset collected from 47 healthy adult subjects.

These healthy subjects were non-smokers with no symptoms of nasal obstruction and/or congestion, and all had Nasal Obstruction Symptom Evaluation score of 30.^(30, 31) This cohort comprised 19 males and 28 females, with a mean (standard deviation; SD) age of 48 (SD=18) years. Computed mean (SD) values on the less patent unilateral nasal cavity of these subjects were 6.4 (SD=1.5) L/min for unilateral airflow rate; 39.0% (SD=8.2%) for airflow partition; and 44.0 (SD=10.0) cm² for unilateral SAHF50. Mean (SD) values on the more patent unilateral nasal cavity of these subjects were 10.1 (SD=2.4) L/min for unilateral airflow rate; 61.0% (SD=8.2%) for airflow partition; and 55.0 (SD=11.0) cm² for unilateral SAHF50. These ranges, mean (SD) served as healthy reference thresholds for CFD-derived computed variables used in comparisons with pre- and post-surgery models, as well as 7 “stepwise virtual surgery” models for Subjects 1 and 2. The predominately obstructed side from NAO subjects was compared with the less patent side of healthy cohort, and less obstructed side for NAO subject with more patent side in healthy cohort.

RESULTS

Subject 1 - Assessment of Nasal Models:

Computed values of airflow rate, airflow partition and SAHF50 on the *predominately obstructed side* from this subject’s pre-surgery model were below the lower threshold (Mean-SD) of healthy subjects (Fig. 2). On the contrary, computed values from post-surgery model were within reference threshold (Mean± SD) of healthy subjects for airflow rate and SAHF50, and was marginally above the upper threshold (Mean+SD) of healthy subjects (Fig. 2). Among “stepwise virtual surgery” models, airflow rate for SEP-UIT, BIT, OIT and SEP were within reference threshold of healthy subjects; while SEP-BIT and SEP-OIT were slightly above the upper threshold (Fig. 2A). For airflow partition, SEP-BIT, SEP-UIT, BIT and OIT within reference threshold of healthy subjects; and SAHF50 for all “stepwise virtual surgery” models involving septoplasty (SEP, SEP-UIT, SEP-OIT and SEP-BIT) were within the reference range (Fig. 2C).

On the *less obstructed side* (Fig. 3), this subject’s pre-surgery model was within the reference range of healthy subjects across all three CFD-derived computed variables. The post-surgery model was within reference range for airflow rate and SAHF50, and marginally off the lower threshold of healthy subjects for airflow partition. All virtual surgery models were within reference range for airflow rate and SAHF50 (Figs. 3A & 3C). With exception of SEP-OIT and UIT, virtual surgery models were within reference range for airflow partition; SEP-OIT was below lower threshold of healthy subjects and UIT above upper threshold (Fig. 3B). Note that the virtual surgery procedure model that most resembled the actual type of surgery this subject had was SEP-UIT.

Subject 2 - Assessment of Nasal Models:

Computed results on the *predominately obstructed side* showed that this subject’s pre-surgery model was subpar across all three CFD-derived computed variables (Fig. 4). The post-surgery model was within reference range for airflow rate and SAHF50 (Figs. 4A & 4C), and above the upper threshold of healthy subjects (Fig. 4B). For “stepwise virtual surgery” models, SEP was within airflow rate reference range, and SEP-UIT at the upper

boundary of the reference threshold of healthy subjects. In addition, SEP-UIT was the only model within airflow partition reference range, while SEP and SEP-UIT fell within reference range for SAHF50 (Fig. 4C).

Pre- and post-surgery models were below the unilateral airflow reference range on the *less obstructed side* (Fig. 5A). Post-surgery model was below reference range on this side of the nasal cavity for all computed variables, while pre-surgery model was only within SAHF50 reference range. Among “stepwise virtual surgery” models, SEP and UIT are the only models that failed to meet reference threshold for airflow rate; and one model (SEP-UIT) was within airflow partition reference threshold. In contrast to airflow rate and airflow partition, all virtual surgery models were with reference threshold of healthy subjects for SAHF50. Note that virtual surgery procedure for SEP was most similar to the actual surgery that was performed on this subject.

DISCUSSION

The various “stepwise virtual surgery” procedures performed in the current work are different from the “virtual surgeries” implemented in our previous studies.^(11, 12, 22) The procedures here represent possible surgical techniques for inferior turbinectomy as opposed to reproducing the actual procedures that each patient underwent. In Rhee and colleagues,^(11, 12) the goals were to compare computed airflow-related values from virtual surgery models comprising unilateral inferior turbinectomy, septoplasty, and septoplasty with inferior turbinectomy to actual post-operative computed outcomes; and to quantify the effects of the following individual procedures on nasal airway patency, nasal valve repair, bilateral inferior turbinectomy, and septoplasty. Our goal in Frank-Ito et al.⁽²²⁾ was to demonstrate that the surgeon could digitally reproduce the procedure performed in the patient. The goal of our present work was to compare how well different surgical procedures restore nasal patency to predefined reference ranges for CFD-derived computed variables that correlated with patient-reported scores of good surgical outcomes.

Computed results for Subject 1 suggest that virtual surgery models, SEP and SEP-UIT were within healthy reference thresholds (Mean±SD) on both sides of the nasal cavity and across all three CFD-derived computed variables. If we adjust for complexity of surgery, our results point toward SEP as the recommended surgical technique for this subject. Contrary to Subject 1, no virtual surgery procedure had all CFD-derived computed variables within healthy reference thresholds in Subject 2. Nonetheless, our results indicate that SEP-UIT will be the preferred procedure for this subject, followed by SEP. Two of three computed variables for SEP-UIT were within reference thresholds of healthy subjects on the predominately obstructed side, and all three computed variables were within reference thresholds on the less obstructed side.

The analyses and methods presented here aim to provide important preliminary insights into the following questions: [1] Can surgeons use virtual surgery techniques to design surgical approaches that normalize nasal physiology (as measured by CFD-derived measures of nasal patency)? [2] What individual surgical procedure (inferior turbinectomy or septoplasty) or combination of procedures is the most effective to bring objective measures into normative

range? Furthermore, by comparing the results of the “stepwise virtual surgery” models with the subject’s actual surgery, we can answer these questions: [3] In patients with good outcomes (normal patient-reported scores), can the same improvement in nasal physiology be achieved with less surgery? [4] In patients with poor outcomes (abnormal patient-reported scores), could a different surgical technique provide greater improvement in nasal physiology? At the same time, it is necessary to note that current virtual surgical methods still lack adequate user-friendly platform needed for surgeons to utilize. The potential abilities and current limitations of CFD virtual surgery models to accurately capture surgical changes performed during actual NAO surgeries were highlighted in our previously published work.⁽²²⁾

With regard to assessing nasal patency for NAO, several objective tools have been used to evaluate nasal physiology.⁽³²⁾ The most important are rhinomanometry, which measures nasal resistance, and acoustic rhinometry, which measures airspace cross-sectional areas.⁽³³⁾ Both tools have been used extensively to investigate surgical outcomes,⁽³⁴⁾ effects of decongestant drugs on nasal patency,⁽³⁵⁾ and normal nasal physiology,⁽³⁶⁾ including the nasal cycle.⁽³⁷⁾ Unfortunately, due to their poor correlation with patients’ symptoms, none of the objective tools currently available can be used to predict the outcome of nasal surgery.⁽³⁸⁾ In addition, several research groups have developed computer models of the human nasal passages aimed at investigating the aerodynamic consequences of abnormal nasal anatomy,^(39–41) surgery,^(15, 21, 42–47) or creating template models of the healthy nasal anatomy.^(48–50) These studies have demonstrated the ability of CFD to describe accurately the dynamics of nasal airflow and the relationship between morphology and function. However, no CFD study until now has systematically investigated individual (turbinectomy or septoplasty) procedures and combined turbinectomy and septoplasty procedures, while accounting for the complexity of these procedures in restoring nasal patency to some healthy ranges. In particular, the hierarchical “stepwise virtual surgery” approach implemented in this work has merit in surgical planning cases where surgical decision is difficult or in cases where primary surgery failed to correct NAO symptoms, warranting the possibility of revision surgery.

CONCLUSIONS

This preliminary study involving two NAO subjects uses CFD modeling to demonstrate a methodological approach of assessing efficacy of individual (turbinectomy or septoplasty) procedures and combined turbinectomy and septoplasty procedures in restoring NAO to predefined baseline nasal patency levels. To do this, hierarchical “stepwise virtual surgery” 3D nasal models spanning “unilateral inferior turbinectomy” to “septoplasty with bilateral inferior turbinectomy” were created in both subjects. Steady-state laminar incompressible inspiratory airflow and heat transfer simulations were conducted in the pre- and post-surgery models, as well as across all 7 “stepwise virtual surgery” models. In Subjects 1, all computed values for SEP-UIT and SEP virtual models were within healthy subjects’ reference ranges. In Subjects 2, SEP-UIT was the best virtual surgery model. Results from the current study will lay the foundation for a future study with a larger cohort of subjects. A larger cohort study will help identify “stepwise virtual surgery” models that consistently

bring CFD-derived computed variables into normative ranges, as well as potentially identify safe limits on these surgical techniques.

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Figure 1:

Digital modifications on Subject 1 nasal anatomy implemented in creation of “stepwise virtual surgery” procedures. *TOP PANEL:* (A) Pre-surgery nasal airspace in blue mask at a region turbinectomy was done; (B) 2-pixel dilation in green mask along predominately obstructed side inferior turbinate showing turbinectomy; (C) 2-pixel dilation in peach mask along less obstructed side inferior turbinate showing turbinectomy; (D) 2-pixel dilation along both inferior turbinates showing bilateral turbinectomy; (E) Pre-surgery nasal airspace at a region septoplasty was done; (F) Purple mask showing septum region septoplasty was done; (G) Green outline of septum after septoplasty; and (H) Nasal airspace after septoplasty. *BOTTOM PANEL:* Nasal airspace pre-surgery, post-surgery and after “stepwise virtual surgery” procedures. Procedure acronyms are defined in Table 1.

Figure 2:

Bar plots depicting computed results on the *predominately obstructed side in Subject 1*. Bars represent pre-surgery model, post-surgery model and all “stepwise virtual surgery” models, as well as mean values for 47 healthy subjects. Vertical dash lines indicate lower reference threshold (Mean-SD) and upper reference threshold (Mean+SD) ranges computed from the 47 healthy subjects. (A) Unilateral airflow rate; (B) Airflow partition; and (C) Surface area where heat flux density is greater than 50 W/m² (SAHF50).

Figure 3:

Bar plots depicting computed results on the *less obstructed side in Subject 1*. Bars represent pre-surgery model, post-surgery model and all “stepwise virtual surgery” models, as well as mean values for 47 healthy subjects. Vertical dash lines indicate lower reference threshold (Mean-SD) and upper reference threshold (Mean+SD) ranges computed from the 47 healthy subjects. (A) Unilateral airflow rate; (B) Airflow partition; and (C) Surface area where heat flux density is greater than 50 W/m² (SAHF50).

Figure 4:

Bar plots depicting computed results on the *predominately obstructed side in Subject 2*. Bars represent pre-surgery model, post-surgery model and all “stepwise virtual surgery” models, as well as mean values for 47 healthy subjects. Vertical dash lines indicate lower reference threshold (Mean-SD) and upper reference threshold (Mean+SD) ranges computed from the 47 healthy subjects. (A) Unilateral airflow rate; (B) Airflow partition; and (C) Surface area where heat flux density is greater than 50 W/m² (SAHF50).

Figure 5:

Bar plots depicting computed results on the *less obstructed side in Subject 2*. Bars represent pre-surgery model, post-surgery model and all “stepwise virtual surgery” models, as well as mean values for 47 healthy subjects. Vertical dash lines indicate lower reference threshold (Mean-SD) and upper reference threshold (Mean+SD) ranges computed from the 47 healthy subjects. (A) Unilateral airflow rate; (B) Airflow partition; and (C) Surface area where heat flux density is greater than 50 W/m² (SAHF50).

Table 1:

Surgical procedures that were modeled via “stepwise virtual surgery”. These individual surgeries and combinations of surgeries are part of the portfolio of surgical techniques available to ear-nose-throat surgeons. CR = Complexity rank. CR is determined by estimating standard surgical operative time of each procedure. Rank of 1 indicate least complex procedure and 5 for most complex procedure.

Procedure Classification	Procedure	Procedure Acronym	Complexity Rank
Individual Procedures	Unilateral inferior turbinectomy on predominately obstructed side	OIT	1
	Unilateral inferior turbinectomy on less obstructed side	UIT	1
	Septoplasty	SEP	3
Combined Procedures	Bilateral inferior turbinectomy	BIT	2
	Septoplasty with unilateral inferior turbinectomy on predominately obstructed side	SEP-OIT	4
	Septoplasty with unilateral inferior turbinectomy on less obstructed side	SEP-UIT	4
	Septoplasty with bilateral inferior turbinectomy	SEP-BIT	5

Table 2:

Pressure drop (Pascal) from nostrils to choana and from nostrils to outlet.

Procedure	Procedure Acronym	Subject 1 Pressure (pa)		Subject 2 Pressure (pa)	
		Choana	Outlet	Choana	Outlet
Pre-Surgery	PRE	17.41	36.12	19.31	23.72
Post-Surgery	POST	17.42	34.45	19.34	25.79
Unilateral inferior turbinectomy on predominately obstructed side	OIT	17.62	21.03	19.35	24.73
Unilateral inferior turbinectomy on less obstructed side	UIT	17.60	21.02	19.34	28.04
Septoplasty	SEP	17.54	21.84	19.34	30.25
Bilateral inferior turbinectomy	BIT	17.58	22.00	19.32	28.54
Septoplasty with unilateral inferior turbinectomy on predominately obstructed side	SEP-OIT	16.69	21.47	19.39	35.31
Septoplasty with unilateral inferior turbinectomy on less obstructed side	SEP-UIT	17.55	22.72	19.36	35.98
Septoplasty with bilateral inferior turbinectomy	SEP-BIT	17.54	23.52	19.36	41.18