Toward Personalized Nasal Surgery Using Computational Fluid Dynamics

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Objective: To evaluate whether virtual surgery performed on 3-dimensional (3D) nasal airway models can predict postsurgical, biophysical parameters obtained by computational fluid dynamics (CFD).

Methods: Presurgery and postsurgery computed tomographic scans of a patient undergoing septoplasty and right inferior turbinate reduction (ITR) were used to generate 3D models of the nasal airway. Prior to obtaining the postsurgery scan, the presurgery model was digitally altered to generate 3 virtual surgery models: (1) right ITR only, (2) septoplasty only, and (3) septoplasty with right ITR. The results of the virtual surgery CFD analyses were compared with postsurgical CFD outcome measures including nasal resistance, unilateral airflow allocation, and regional airflow distribution.

Results: Postsurgery CFD analysis and all virtual surgery models predicted similar reductions in overall nasal resistance, as well as more balanced airflow distribution between sides, primarily in the middle region, when compared with the presurgery state. In contrast, virtual ITR alone produced little change in either nasal resistance or regional airflow allocation.

Conclusions: We present an innovative approach for assessing functional outcomes of nasal surgery using CFD techniques. This preliminary study suggests that virtual nasal surgery has the potential to be a predictive tool that will enable surgeons to perform personalized nasal surgery using computer simulation techniques. Further investigation involving correlation of patient-reported measures with CFD outcome measures in multiple individuals is under way.


Surgical Management of anatomic nasal airway obstruction (NAO) is very common. In 1992, nasal septoplasty and turbinate surgery were reported to be the third and eighth most commonly performed surgical procedures by otolaryngologists, respectively (at a rate of 15 procedures per 10,000 insured patients). In addition, functional septorhinoplasty and nasal valve repair procedures are performed for more complex anatomic deformities. Although a variety of surgical techniques and approaches are available to the surgeon, there is no consensus on any given surgical approach or on how to define the success of a given approach.

One of the greatest challenges in addressing NAO is the lack of correlation between patient-reported symptoms and objective findings. Determining which patients would benefit from surgery as well as selecting a particular surgical approach is primarily based on the clinical assessment and personal experience of the surgeon. Given the subjective nature of the assessment, it is not surprising that reported surgical failure rates are as high as 25% to 50%. The proposed reasons for this finding are multifactorial and complex but include the inability to reliably measure nasal function and airflow as well as inconsistent correlations between patient-reported symptoms with objective testing currently available. In addition, inappropriate patient selection for surgery or choice of surgical approach may contribute to patient dissatisfaction. Therefore, to optimize surgical outcomes, more sophisticated tools are needed that would enable surgeons to better assess the nasal airway, identify patients who would potentially benefit from surgery, and determine the optimal surgical intervention.

The complexity of the nasal airway is well suited to the creation of a computational tool to aid surgeons in the diagnosis and treatment of NAO. With the availability of powerful bioengineering computer-aided design software, anatomically accurate 3-dimensional (3D) computational models can now be generated from computed tomography (CT) or magnetic resonance imaging (MRI) data. Computational fluid dynamics (CFD) soft-
ware can be used to analyze these models and calculate various anatomic and physiologic measures including nasal airflow, resistance, air conditioning, and wall shear stress. Furthermore, these 3D computational models can be modified to simulate surgical changes (ie, virtual surgery). Then, CFD tools can be used to study the effects of these changes on nasal function and potentially predict surgical outcomes.

This article presents early data from an ongoing 4-year prospective study designed to investigate the relationships between nasal cavity CFD modeling and patient-reported subjective measures of nasal obstruction. The objective of this initial study was to evaluate the ability of CFD modeling to predict actual surgical outcomes using a virtual nasal surgery computational model. This was accomplished by comparing quantitative CFD parameters (nasal resistance and inspiratory airflow allocation) between an actual postsurgery model and 3 different virtual surgery models. We hypothesized that virtual surgery CFD results would predict postsurgical CFD results with some variability owing to differences in the mechanics of the actual surgical steps and the way these steps were translated to the computer model and owing to possible random effects of postsurgical healing.

**PATIENT METHODS**

Patients are being recruited from the Medical College of Wisconsin (MCW) Otolaryngology clinic as part of our larger 4-year prospective study. Inclusion criteria include age 15 years or older and having a clinical diagnosis of a nonreversible, surgically treatable cause of nasal obstruction (deviated septum, turbinate hypertrophy resistant to medical treatment, or lateral wall collapse). The research protocol was approved by the MCW institutional review board. The patient presented in this article is a 30-year-old, 86.4-kg woman who presented with complaints of NAO and had significant leftward septal deviation with right inferior turbinate hypertrophy.

**PATIENT TREATMENT**

Modified contiguous CT scans in the axial plane of the entire nasal cavity and external nasal soft tissue were performed preoperatively (0.625-mm increments; 0.313-mm resolution) and approximately 6 months postoperatively (0.600-mm increments; 0.313-mm resolution). The decision for the surgical procedure to be performed was made by the surgeon (J.S.R.) based on clinical presentation and the standard of medical care. In this case, the patient underwent septoplasty using standard septoplasty techniques and right inferior turbinate reduction (ITR). The anterior one-half of the inferior turbinate was debulked by performing submucosal resection of the bone and removal of the submucosal tissue with sharp dissection. No thermal or ablative techniques were used. Postsurgical care was performed in the usual manner following nasal surgery with an uneventful postoperative course.

**COMPUTATIONAL FLUID DYNAMICS WORKFLOW**

Our CFD simulation workflow is illustrated in Figure 1. The presurgery and postsurgery computer models were created using the presurgery and postsurgery CT scan image data and the image analysis software Mimics 13.1 (Materialise, Plymouth, Michigan). In addition, the presurgery model was digitally altered using Mimics software to generate 3 virtual surgery models for analysis: (1) right ITR only, (2) septoplasty only, and (3) septoplasty with right ITR (Figure 2). The goal of virtual surgery was to alter the presurgical nasal anatomy to reproduce the anticipated surgical changes. Three-dimensional reconstructions of the nasal septum are shown in Figure 3 and illustrate the virtual surgery and actual postsurgery areas of anatomic change. As per the carefully conceived institutional review
board protocol, the virtual surgery models were created after the actual surgery was performed so that surgical decision making would not be influenced before the ability of CFD to predict patient outcomes has been assessed. Virtual surgery was performed on the presurgery model by the surgeon (J.S.R.) within 24 hours after the actual surgery to minimize recall bias.

To solve the equations that govern fluid flow, each 3D nasal model must be divided into a large number of small cells where air velocity and pressure can be defined. This was accomplished by creating a mesh with approximately 4 million tetrahedral cells using ICEM-CFD (ANSYS Inc, Canonsburg, Pennsylvania). Steady-state inspiratory airflow simulations were conducted using Fluent 12.0 (ANSYS Inc, Lebanon, New Hampshire) for airflow rates corresponding to normal resting breathing. The following boundary conditions were used in Fluent to determine the airflow field: (1) a “wall” condition (zero velocity, stationary wall assumed) at the airway walls, (2) a “pressure-inlet” condition at the nostrils with gauge pressure set to 0, and (3) a “pressure-outlet” condition at the outlet with gauge pressure set to a negative value in Pascals that generated the target steady state flow rate of 15.7 L/min. This flow rate represents an estimate of twice the patient’s minute volume (amount of air exhaled in 1 minute) based on allometric scaling by body weight.\(^7\) Additional details on the differential equations, computational algorithms, and air physical properties used can be found in previous publications by our group.\(^8\) Figures, printouts, diagrams, and other visualizations of CFD model results were made using the visualization software package Fieldview (Intelligent Light, Lyndhurst, New Jersey) as well as the visualization capabilities within Fluent.

OUTCOME MEASURES

The outcome measures calculated by CFD included nasal resistance, airflow allocation, and regional airflow distribution within the nasal cavity. Nasal resistance was calculated as \(\Delta p/Q\), where \(\Delta p\) is the pressure difference in Pascals between the nostrils and posterior nose and \(Q\) is the flow rate in milliliters per second. For consistency among models and CT scans, the posterior nose where pressure was measured for calculating nasal resistance was defined as the posterior end of the nasal septum. Airflow allocation measured the percentage of total airflow passing through the left and right nasal cavities. Regional airflow distribution was analyzed through visualization of major inspiratory streamlines and quantified by allocation of volumetric flow to dorsal, middle, and ventral portions of a mid-turbinate coronal cross-section, as described by Subramaniam and colleagues.\(^9\)

RESULTS

NASAL RESISTANCE

Before surgery, overall nasal resistance was 0.060 Pa/ (mL/s), and unilateral right and left nasal resistances were 0.096 Pa/(mL/s) and 0.160 Pa/(mL/s), respectively (Figure 4A). Virtual septoplasty with right ITR resulted in a reduction of the overall nasal resistance to 0.046 Pa/(mL/s), while the actual surgery resulted in a reduction of the overall nasal resistance to 0.039 Pa/(mL/s). Virtual septoplasty alone reduced overall nasal resistance to 0.047 Pa/(mL/s) and right ITR alone did not affect the overall nasal resistance.

Both virtual and actual surgery resulted in decreases in unilateral nasal resistances; however, the effect was more pronounced on the patient’s left side, which was affected by the septal deviation. Virtual septoplasty with ITR resulted in a left-sided nasal resistance of 0.098 Pa/ (mL/s) and actual postsurgery left-sided nasal resistance was 0.072 Pa/(mL/s). Virtual septoplasty alone, with
Virtual surgery models predicted a more balanced airflow distribution between the dorsal, middle, and ventral regions of the nose on the right (A) and left (B) sides. ITR indicates inferior turbinate reduction.

Figure 5. Computational fluid dynamics (CFD)—calculated regional airflow distribution between the dorsal, middle, and ventral regions of the nose on the right (A) and left (B) sides. ITR indicates inferior turbinate reduction.

a left-sided nasal resistance of 0.098 Pa/(mL/s), accounted for almost all of the drop in resistance on that side.

AIRFLOW ALLOCATION

The presurgery CFD model estimated that 61.3% of the total airflow passed through the right side, while 38.7% passed through the left. The postsurgery and virtual surgery models predicted a more balanced airflow distribution between the 2 sides (Figure 4B). The virtual septoplasty with ITR model and the septoplasty only model resulted in a very similar distribution. In contrast, the ITR-only model did not alter the airflow allocation between sides to a great degree with 61.7% of the airflow passing through the right and 38.3% through the left. The actual postsurgery CFD model resulted in an airflow allocation slightly favoring the left side when compared with the CFD-predicted results for the virtual surgery models. Differences in airflow allocation between the actual postsurgery and virtual surgery models may have been due to the nasal cycle, since presurgery and postsurgery CT imaging suggested that the patient was cycling on opposite sides when the 2 CT scans were taken.

REGIONAL AIRFLOW DISTRIBUTION

In the presurgery CFD model, the majority of the airflow passed through the right middle region. In contrast, the postsurgical model showed more balanced airflow through the right and left sides with increased airflow through the left middle region and minimal dorsal airflow (Figure 5). The 2 virtual surgery models that included septoplasty showed a similar increase in left middle airflow and slightly decreased right middle airflow, although these changes were less in magnitude than the actual postsurgical results. The virtual ITR-only model shows negligible change in regional airflow allocation when compared with the presurgery model.

As part of an ongoing 4-year prospective study, we have presented a case report of virtual nasal surgery and CFD techniques applied to computational models generated from a patient with NAO secondary to septal deviation and inferior turbinate hypertrophy. A complete comparison between the presurgery and actual postsurgery CFD results and correlation with patient-reported measures will be reported in a future publication. The focus of this study was to establish the potential application of virtual nasal surgery and determine the predictive utility of virtual surgery CFD modeling with respect to actual postsurgical outcomes.

To date, relatively little research has been published in the area of virtual nasal surgery. Although no other study has compared virtual nasal surgery CFD results with actual postsurgical outcomes, CFD techniques have been increasingly used to study various simulated alterations of the human nasal airway over the past decade. Some authors have described simulated nasal surgery procedures using computerized models, typically by using CT scans from subjects with normal nasal anatomy, which are then altered to create a “virtual surgery” nasal model with the appropriate modifications.10-12 Others have altered computer models with abnormal anatomy to assess postoperative effects but these have not been compared with actual postsurgical results, therefore limiting the generalizability of these results.13

Wexler et al18 investigated the changes in unilateral nasal airflow by modeling the circumferential removal of 2 mm of soft tissue along the left inferior turbinate in a computational model generated from a healthy subject without nasal complaints. Another group used imaging from a cadaver with septal deviation and concha bullosa to generate a computational model.13 These authors simulated a virtual septoplasty and partial lateral turbinectomy and compared CFD-calculated airflow and nasal resistance results between the before and after virtual surgery models. In addition to studying nasal airflow patterns, CFD has been used to investigate nasal air conditioning following simulated unilateral resection of the inferior and middle turbinates.13 Garcia et al14 used 3D software tools on a healthy nose model to create septal deviations in various locations and applied CFD techniques to study the effects on nasal resistance.

Overall, the virtual surgery results are promising and demonstrate the potential of CFD techniques to predict postsurgical outcomes. The CFD calculations of overall nasal resistance for the combined virtual septoplasty with ITR model correlated well with the actual postsurgery calculations. Of the 3 virtual surgery models, the virtual
septoplasty with ITR model predicted the lowest overall nasal resistance. Interestingly, results from the various virtual surgery combinations suggest that ITR may have contributed very little to the reduction of overall nasal resistance in this patient, for whom septal deviation was likely the major contributing factor to nasal resistance. Prior studies, such as that done by Wexler et al,10 have supported a decrease in nasal resistance following ITR; however, this was based on a unilateral analysis only, conducted in a normal airway. In the present study, unilateral nasal resistance also decreased in the virtual surgery and actual postsurgery models.

Airflow allocation results illustrate the improved balance of airflow between the left and right sides compared with presurgery. Virtual septoplasty with and without ITR demonstrated similar changes in allocation between sides, while the virtual ITR only model showed no difference compared with presurgery. This seems to predict that right ITR alone has a negligible impact on airflow allocation between the left and right sides of the nose. This analysis suggests that septoplasty alone could achieve improved airflow allocation without the need for ITR for this patient.

Regional airflow distribution results from the virtual surgery models also showed reasonable correlation with the postsurgery results and allow for more detailed understanding of airflow changes within the nasal cavity as a result of surgery. Here, the general trends reported in Figure 5 are likely more indicative of the anticipated surgical outcome than the absolute numbers obtained by CFD simulations. Presurgery analysis shows that airflow was restricted in the left middle region due to the large leftward septal deviation. Results of subsequent virtual septoplasty with and without ITR and the final postsurgery model show noticeable improvement in left middle region airflow with concomitant decrease in right middle airflow to yield a more balanced flow. Again in this analysis, virtual right ITR did not dramatically change regional airflow distribution, suggesting minimal impact from this procedure.

If this type of modeling were used in a presurgery planning situation, the virtual surgery models suggest that right ITR, using this particular surgical technique, may have negligible impact on the improvement of symptoms in this particular patient. Compensatory turbinectomy hypertrophy in the setting of nasal septal deviation is thought to protect the more patent nasal passage from the drying and crusting effects of increased airflow.15 Findings from histologic analysis of the hypertrophied inferior turbinate have shown that enlargement of the bony layer contributes to 75% of the enlargement of the turbinate as compared with the mucosal layer.15 The decision to perform turbinectomy reduction is typically based on the surgeon's clinical judgment, and the exact method may vary from surgeon to surgeon. Studies looking at outcomes of turbinectomy combined with septoplasty have shown variable results, and there is no consensus at this time.6,10,16-18 The use of CFD modeling for surgical planning could help determine which patients may benefit from ITR in the setting of septal deviation. In this particular patient case, the use of presurgical CFD planning may have changed the decision to perform ITR using this particular surgical technique, since simulations would have predicted little impact on nasal resistance.

While CFD applications for nasal surgery are certainly promising, there are several inherent limitations in the current state of this technology. Computational fluid dynamics modeling techniques rely on several assumptions to simplify the computational process. These include the use of a fixed wall model, which cannot account for compliance of the nasal soft tissues in the presence of negative pressure. In addition, these models assume that complete airflow occurs through the nose only, when in reality patients with varying degrees of NAO will breathe through the mouth, potentially altering the true airflow characteristics in the nose. Another modeling challenge is that each computational model represents the nasal anatomy at a specific point in time. While major structural features will generally be preserved across models, the dynamic nature of the nasal mucosa (ie, nasal cycling) can vary between models of the same patient and potentially influence direct comparisons. This has the potential to become problematic when applying CFD techniques to the relatively narrow nasal passages, where only a few millimeters of mucosal swelling can result in significant airflow changes. In addition, although virtual surgery can be done on a static model, the unpredictable and dynamic nature of patient healing can ultimately limit the predictive capability of the model. In addition, important practical considerations include the fact that while CFD software applications have become more widely available and accessible, they remain costly and are often cumbersome to use. Also, the workflow to create computational models and run various simulations is also very time consuming and requires a level of technical expertise that is not available to most surgeons.

As we look to the future, the hope is that this technology can be more routinely used day to day in the armamentarium of otolaryngologists and facial plastic surgeons. At this time, CFD technology is truly translational in nature and will require further research and development to reach its full potential for future applications. In the meantime, the collection of normative CFD models that is accruing in the literature will be important for comparison purposes and could be used to help set normal ranges for calculated CFD parameters. We envision a future where a virtual nasal surgery software application using a simplified user interface could be coupled with a sophisticated computational component that is largely transparent to the end-user surgeon. This would allow for the rapid creation of computational models “on-the-fly” using readily available CT imaging data. Using these models, the surgeon could perform an in-office CFD analysis of the patient’s nasal airway and simulate various surgical approaches or maneuvers to create a personalized surgical plan for each patient that would provide the best surgical outcome.

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REFERENCES


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