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ORIGINAL INVESTIGATION Rhinoplasty

Comparing Patient-Reported Outcomes with Computational Fluid Dynamics-Derived Nasal Airflow After Nasal Airway Surgery: Prioritizing the Patient's Perception of Nasal Obstruction

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Abstract

Background: Some patients report persistent nasal obstruction after surgical treatment despite objective improvement.

Objective: To compare patients' perceptions of nasal obstruction after surgery with objective nasal airflow as determined by computational fluid dynamics (CFD) modeling: (1) Is perception driven by a more symptomatic side? (2) Can symptom improvement be predicted with CFD modeling?

Methods: Pre/postoperative Nasal Obstruction Symptom Evaluation (NOSE) and visual analog scale (VAS) score were collected for patients undergoing nasal obstruction surgery. Pre/postoperative computed tomography was used to generate patient-specific airway models for CFD simulation at 15 L/min resting inspiration.

Results: Ten patients (22–53 years, seven men and three women) underwent septoplasty, turbinate reduction, and/or rhinoplasty. Postoperative NOSE was most correlated with postoperative VAS score from the "affected" side ($R^2 = 0.59$, $p < 0.01$), and postoperative NOSE was strongly predicted by a two-parameter model using parameters only from the "affected" side ($R^2 = 0.84$, adjusted $R^2 = 0.80$, $p < 0.01$).

Conclusion: The postoperative state of the initially "affected" side drives outcomes after nasal obstruction surgery. Surgeries should prioritize improving the "affected" side. A two-parameter model using the VAS and nasal airflow from only the "affected" side strongly predicts NOSE and is promising for the future using virtual planning to individualize procedures to optimize outcome.

Introduction

Nasal airway obstruction (NAO) is a debilitating condition impacting sleep, exercise, and quality of life.[1–3] The etiology is often structural, and surgery aims to treat the underlying anatomical deformity: often septal deviation, turbinate hypertrophy, and nasal valve collapse.[4] A wide variety of subjective and objective assessments are available to assess postoperative outcomes,[5–12] but, to date, there is no gold standard.[6,13,14] Although the majority of patients experience subjective improvement after surgery for nasal airway obstruction, some require revision surgery for persistent symptoms.[15–17] In other cases, the etiology of persistent symptoms remains unclear, and patients may report no symptomatic change despite objective improvement.[18,19] Determining who benefits from surgical correction of nasal obstruction is limited by the poor correlation between various nasal airway obstruction assessments, and the leading factors driving symptom

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KEY POINTS

Question: After surgery for nasal obstruction, is the state of the initially more bothersome side or the objectively more constricted side more important for predicting nasal obstruction symptoms?

Findings: The postoperative state of the initially more bothersome side is more important for predicting nasal obstruction symptoms.

Meaning: Surgeries for nasal obstruction should focus on improving the initially more bothersome side rather than prioritizing symmetry.

severity remain unclear. A refined understanding of how the nasal airway translates into the perception of nasal airway obstruction is necessary.

For most patients with nasal airway obstruction, there is an "affected," more symptomatic side.[20,21] Recent studies have focused on unilateral nasal cavity analysis to better understand the relevance of the "affected" side.[9,21–23] Preliminary studies posit that (1) the "affected" side or (2) the degree of symmetry between the "affected" and the "unaffected" sides may drive symptom severity.[21–23] However, these studies have been limited in sample size and have not explored the postoperative state.

Computational fluid dynamics (CFD) modeling is a technique well-suited for analyzing unilateral nasal airflow, using computed tomography (CT) to reconstruct patient-specific anatomy and generate airflow parameters.[22,24–40] To that end, the purpose of this study was to use the CFD technique to investigate the primary factors affecting postoperative perception of nasal obstruction. Among patients with unilateral nasal obstruction who underwent nasal airway surgery, the nasal airflow as predicted by CFD was compared with the patient's perception of nasal airflow as measured by patient-reported outcome measures (Nasal Obstruction Symptom Evaluation [NOSE] and visual analog scale [VAS]). However, recent attempts to correlate subjective scores with single objective parameters have met inconsistent results.[12,18,23,33,41,42] Given the complexity of nasal obstruction, we hypothesize that subjective NAO scores are unlikely to correlate reliably with a single CFD parameter. As such, a secondary purpose was to develop a multiparameter model for postoperative NAO symptoms reported by patient-reported outcome measures, as predicted by CFD analysis.

Methods

Patient enrollment and outcome measures

Ten subjects (age 22–53 years old, seven men and three women) who underwent surgery for nasal airway obstruction at a tertiary medical center were included in the final analysis. Exclusion criteria included nasal obstruction from nonanatomical factors (infectious, inflammatory, neoplastic, or autoimmune) or prior nasal surgery. In addition, patients were screened for obvious changes in mucosal thickness between pre- and postoperative CT images to control for nasal cycling, which can dramatically impact CFD-derived results. Patients with CT evidence of nasal cycling were eliminated to ensure that intrasubject and intersubject comparisons would not be influenced by nasal cycling, thus avoiding potential confounding. Surgeries were performed by a single surgeon and reflect the standard of care for management of the relevant anatomical obstruction (Supplementary Table S1). Methods were institutional review board approved, and informed consent was obtained prior to enrollment; details are described in a prior study.[33,43,44] In brief, pre- and postoperative (between 3 and 9 months after surgery) clinical surveys for nasal obstruction were administered, and pre- and postoperative high-resolution CT imaging was obtained (0.6 mm slice increments, 0.313 mm resolution). Clinical surveys were the NOSE, a five-domain quality of life survey for nasal airway obstruction scored 0–100 (higher score indicating worse obstruction) that has been used to grade nasal airway obstruction severity,[5] and the VAS, scored 0–10, to grade unilateral nasal airway obstruction severity (higher score indicating worse obstruction).

Computational fluid dynamics modeling

Pre- and postoperative nasal airspaces were segmented by thresholds with manual tuning as needed to reconstruct realistic patient-specific airway models.[23,27,33,35,43,44] The three-dimensional models were imported into ICEM-CFD™ 19.0 (ANSYS), where meshes were generated containing approximately four million tetrahedral cells with finer three-layer prismatic elements having 0.1 mm thickness per layer at the airway walls to accurately account for the near-wall velocity profile. Models were imported into Fluent 19.0 (ANSYS), and airflow simulations were performed by numerically solving the conservation of mass and momentum steady state governing equations for laminar, viscous, incompressible, and inspiratory flow defined as

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

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

where $\vec{u}$ is the velocity vector field, $\rho = 1.204$ kg/m^3 is the fluid density, $\mu = 1.825 \times 10^{-5}$ kg/m^{-s} is the dynamic viscosity, and p is the pressure. The following boundary conditions were specified: stationary nasal walls with no-slip conditions, atmospheric conditions at the inlet with zero-gauge pressure, and a "mass-flow-outlet" condition at the outlet to target 0.0003 kg/s (15 L/min) to replicate resting inspiration.

Statistical analysis

All data analyses including the generation of summary statistics and multiple linear regressions were performed in MATLAB® (MathWorks, Inc.). Statistical analyses were performed at a significance level of 0.05 and a power level of 0.8. Based on a power analysis using R Statistical Software (v4.3.0, R Core Team 2021) with an anticipated strong effect size, 10 subjects were deemed adequate for two- and three-parameter models. Results are presented with the mean (standard deviation [SD]) when applicable.

Results

Clinical scores

Pre- and postoperative clinical scores are shown in Supplementary Table S1. Overall, NOSE scores decreased by 49 (SD = 28.6) postoperatively; for reference, the minimum clinically important difference (MCID) for NOSE is 24.[45] Eight of 10 patients had a NOSE that decreased by more than the MCID. Preoperatively on VAS, six patients scored the left side as more symptomatic (a higher score) versus four on the right. The mean unilateral VAS score on the more symptomatic side (either left or right) was 7 (SD = 1.1) preoperatively and improved to 3 (SD = 2.5) postoperatively. The mean absolute difference in VAS score between the left and right sides was 4.1 (SD = 2.0) preoperatively and 1.1 (SD = 1.37) postoperatively.

Nasal airflow and velocity

Unilateral nasal airflow and nasal resistance derived from CFD are shown in Figure 1. Preoperative mean unilateral nasal airflow partition was 36.4% on the more constricted side and 63.6% on the less constricted side;

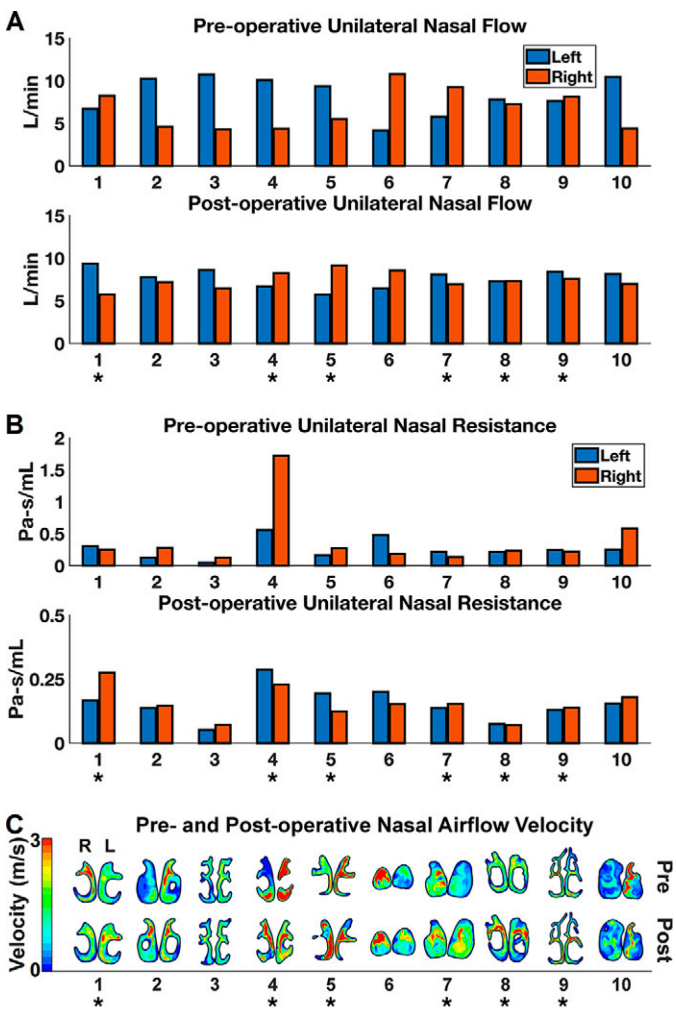

Fig. 1. **(A)** Pre- and postoperative unilateral nasal flow. **(B)** Pre- and postoperative unilateral nasal resistance. **(C)** Nasal airflow velocities through choana cross-sections. Asterisks denote six subjects for whom the preoperative more constricted side becomes the postoperative less constricted side, and vice versa.

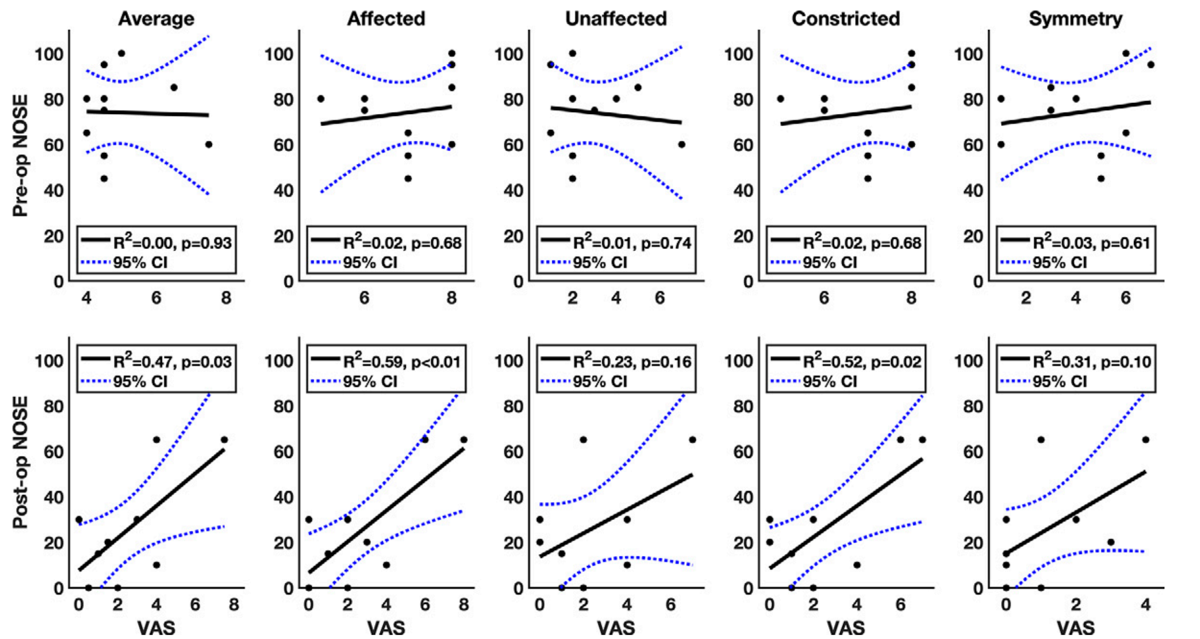

Fig. 2. Pre- and postoperative Nasal Obstruction Symptom Evaluation (NOSE) versus visual analog scale (VAS) score for the average of bilateral nasal cavities, unilateral "affected" side, unilateral "unaffected" side, unilateral more constricted airflow side, and degree of symmetry. Note that, preoperatively, the "affected and constricted" sides are the same for all subjects.

postoperative mean unilateral nasal airflow partition was 44.7% on the more constricted side and 55.3% on the less constricted side (Fig. 1A). Unilateral nasal resistance was inversely related to unilateral nasal airflow, ranging from 0.05 Pa-s/mL to 1.72 Pa-s/mL preoperatively and 0.05 Pa-s/mL to 0.29 Pa-s/mL postoperatively (Fig. 1B).

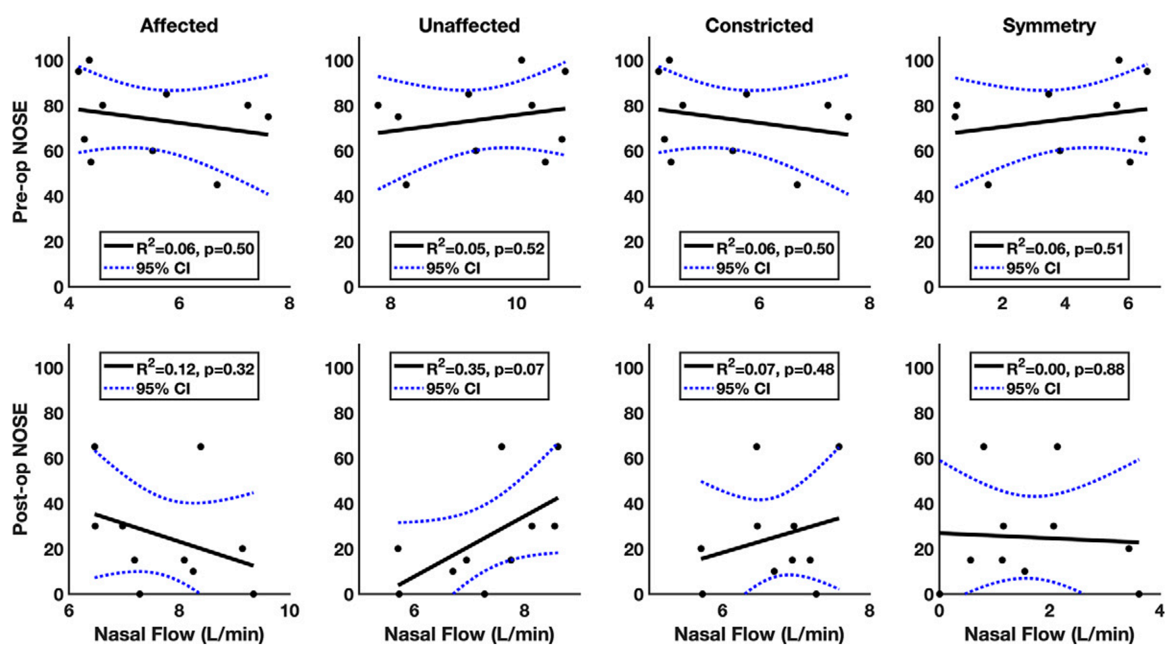

Fig. 3. Pre- and postoperative NOSE versus nasal airflow rate (NF) on the unilateral "affected" side, unilateral "unaffected" side, unilateral more constricted airflow side, and degree of symmetry.

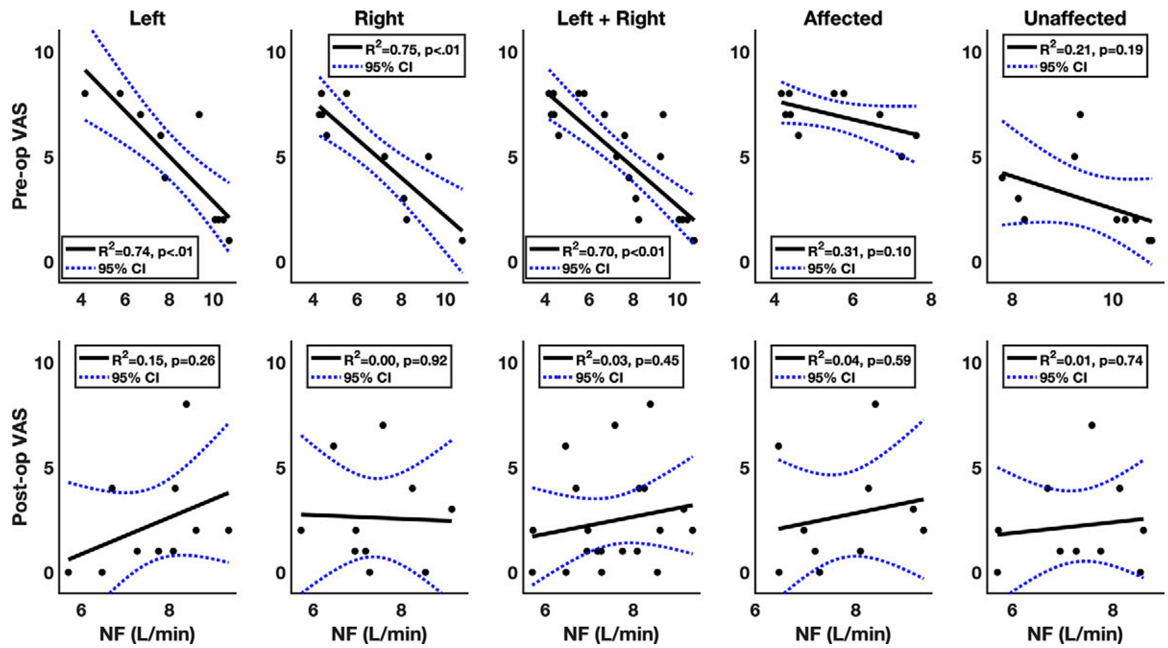

Fig. 4. Pre- and postoperative VAS score versus NF for the left, right, both unilateral (left and right), "affected," and "unaffected" sides.

For six patients, the side of less airflow changed after surgery and became the side of more airflow postoperatively (demarcated by asterisks in Fig. 1).

Correlation between NOSE and VAS and NOSE and nasal airflow

Preoperative NOSE was not correlated with the preoperative VAS score (all $p > 0.05$) (Figs. 2 and 3). However, postoperative NOSE was correlated with postoperative VAS score (Fig. 2); the strongest correlation was with postoperative VAS score on the initial "affected" side ($R^2 = 0.59$, $p < 0.01$), whereas there was slightly weaker correlation with average (of both sides) postoperative VAS score ($R^2 = 0.47$, $p = 0.03$) and no correlation with postoperative degree of symmetry, that is, the absolute difference between left and right VAS score ($p = 0.10$). There was no correlation between pre- or postoperative NOSE and pre- or postoperative unilateral nasal flow (all $p > 0.05$) (Fig. 3).

Correlation between VAS and nasal airflow

The unilateral preoperative VAS score was strongly correlated with unilateral preoperative nasal airflow on both the left and the right sides; this correlation also remained when considering the left and right unilateral airways independently ($R^2 = 0.70$, $p < 0.01$) (Fig. 4). However, there was no correlation between unilateral postoperative VAS score and nasal airflow (all $p > 0.05$) (Fig. 4). There was no correlation between pre- or postoperative VAS score and respective nasal airflow when sorted by the "affected" or "unaffected" side (all $p > 0.05$).

Predictive model for nasal obstruction

Owing to the association between postoperative NOSE score and unilateral nasal obstruction assessments on the initial "affected" side, a two-parameter multiple linear regression model was created based on unilateral VAS score (VAS_{aff}) and unilateral nasal airflow rate (NF_{aff}) only from the "affected" side (Fig. 5A):

$$NOSE_{postop} = \beta_0 + \beta_1 VAS_{aff} + \beta_2 NF_{aff},$$

where the coefficients were $\beta_1 = 7.7$ and $\beta_2 = -11.7$, and β_0 represented the intercept. This model very strongly predicted NOSE score ($R^2 = 0.84$, adjusted $R^2 = 0.80$, $p < 0.01$).

Figure 5B illustrates airflow streamlines in a representative subject (Subject 1) before and after surgery. Pre- and postoperative spatial airflow distributions on the unaffected side showed minimal variation. However, septorhinoplasty had a notably positive impact on postoperative airflow distribution on the affected side.

Discussion

This study used the CFD technique to investigate the primary factors affecting postoperative perception of nasal obstruction. The study population encompassed a wide variety of nasal procedures from septoplasty and

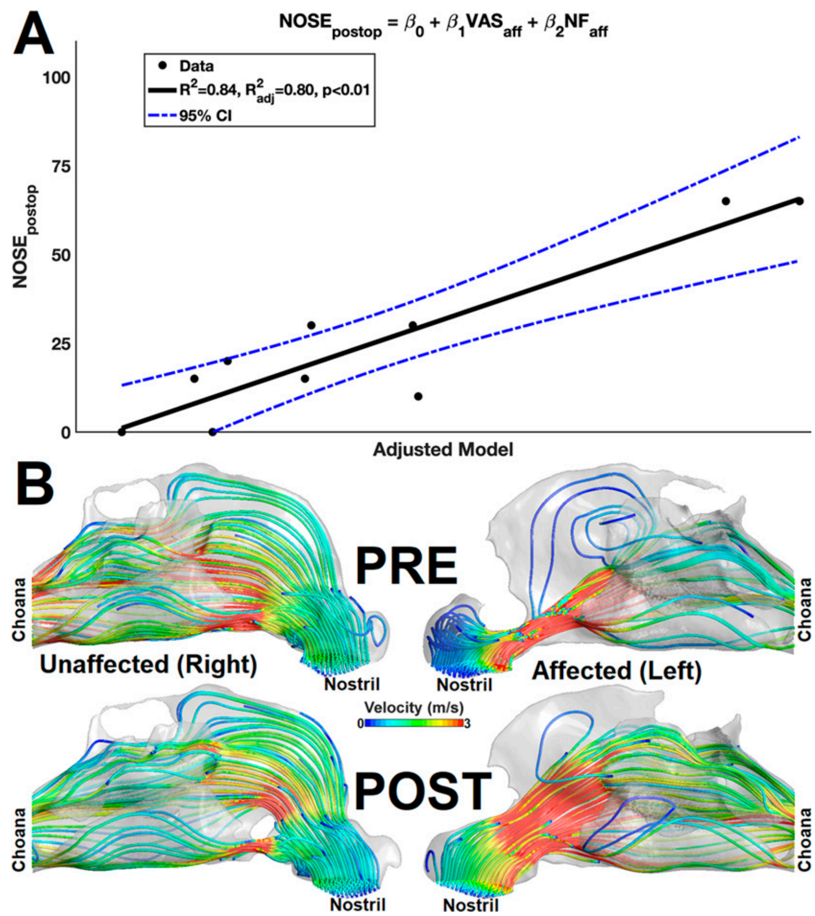

Fig. 5. **(A)** Predictive model for NOSE score. Multiple linear regressions using two parameters, VAS score and NF from the "affected" side, strongly predict NOSE score. **(B)** Airflow streamlines in a representative subject (Subject 1) before and after surgery, with colors indicating velocity magnitude.

turbinate reduction to rhinoplasty with nasal vestibule reconstruction. In this series, the postoperative state of the initial "affected" side appeared to drive postoperative outcome perception. The postoperative VAS score on the initial "affected" side demonstrated the strongest correlation with postoperative NOSE, compared with the VAS score on the objectively more constricted side (determined by CFD) and the degree of symmetry between the left and the right sides. In addition, although all 10 subjects had a postoperative NOSE score that was equal to or less than their preoperative score (suggesting stable to improved symptoms), 2 out of 10 subjects had a NOSE difference of less than the known MCID of 24.[45] Both these patients were within the bottom three with respect to decrease in nasal resistance and increase in nasal airflow on the "affected" side postoperatively; in other words, the patients with the least improvement in nasal airflow specifically on the "affected" side were also the patients without clinically meaningful improvement.

Surgeons often face the challenge of improving unilateral nasal patency on the "affected" side at the expense of the "unaffected" side. Our findings suggest that intraoperatively, if pursuing adequate nasal patency on the "affected" side may narrow the "unaffected" side, surgeons should proceed with prioritizing or overcorrecting the initial "affected" side rather than necessarily seeking to achieve nasal symmetry.

Single parameters that directly assess nasal airflow such as airflow rate and resistance have poorly predicted nasal obstruction quality of life measures.[46] As such, there is growing interest in alternative metrics such as heat flux as potential driving forces behind the perception of nasal patency.[33,47,48] However, there remains a relative scarcity of studies examining the ability of unilateral parameters to explain bilateral nasal symptoms or of multiple parameters to predict nasal symptoms. In this study, a two-parameter model using metrics only from the "affected" side, VAS and CFD-generated nasal airflow, strongly predicted postoperative NOSE scores.

With growing interest in virtual surgery using the CFD technique, the ability to predict postoperative NOSE will be exceedingly important for improving surgical candidacy by identifying patients who are most likely to symptomatically benefit from surgery.

Whereas postoperative NOSE scores were strongly predicted by the model, preoperative NOSE scores were not correlated with any other parameter. One explanation is that preoperative NOSE scores may be more prone to response bias, as these patients are surveyed at the height of symptom severity requiring surgical intervention. On the contrary, the VAS focuses on scoring nasal patency rather than the downstream effects of nasal obstruction on quality of life and thus may be more reliable in the preoperative period. Indeed, left and right preoperative VAS scores were strongly correlated with their respective CFD-derived airflow values. However, preoperative VAS scores sorted by "affected" and "unaffected" sides were not significantly correlated with nasal airflow. This is likely due to the decreased signal-to-noise ratio from the relatively low spread of VAS scores and nasal airflow rates when sorting data by "affected" and "unaffected" sides. This reflects the primary limitation of this study, which is a relatively small sample size. A similar effect is also seen for postoperative VAS scores (also previously reported), which were not correlated with CFD-derived nasal airflow because of the smaller spread of VAS scores in the postoperative state compared with the preoperative state (postoperative VAS score variance = 5.62 vs. preoperative = 6.68; postoperative nasal airflow variance = 1.08 vs. preoperative = 5.67).[41]

Conclusion

Using CFD modeling, this study found that, among patients with nasal airway obstruction who underwent nasal airway surgery, the postoperative state of the initial "affected" (more symptomatic) nasal passage is what primarily drives outcome perception. As such, when faced with establishing a sufficiently patent nasal passage in a narrow nose at the expense of narrowing the contralateral "unaffected" side beyond achieving symmetry, surgeons should prioritize improving the "affected" side. Using the VAS score for nasal patency and nasal airflow from only the "affected" side, a two-parameter model strongly predicted NOSE score. These findings, in conjunction with growing research into CFD-assisted virtual surgery, are promising for a future where presurgical planning can allow individualized surgical technique to optimize nasal obstruction outcomes.

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Authors' Contributions

H.C.: Study conceptualization and methodology development, data analysis, article preparation. D.O.F.-I.: Study conceptualization and methodology development, article reviewing and editing, and project supervision.

Author Disclosure Statement

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Supplementary Material

Supplementary Table S1

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