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WILEY
Nasal Airflow Changes With Bioabsorbable Implant, Butterfly, and Spreader Grafts

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Objective/Hypothesis: Internal nasal valve compromise is a major cause of nasal obstruction, with a growing number of ways to treat this condition. In this study, we compared the effects of butterfly graft, spreader graft, and the bioabsorbable nasal implant on nasal airflow resistance.

Study Design: Cadaver study.

Methods: Computational fluid dynamics (CFD) simulations were completed from nine preoperative and postoperative cadaveric subjects. Each cadaveric head underwent placement of a bioabsorbable nasal implant (BNI) (Spirox Latera; Stryker ENT, Plymouth, MN), butterfly graft, or spreader graft. Pre- and postoperative computed tomography (CT) scans were used to generate three-dimensional models of the nasal airway used in steady-state CFD simulations of airflow and heat transfer during inspiration.

Results: Butterfly graft placement resulted in a mean improvement in nasal airway resistance of 24.9% (±7.3), whereas BNI placement resulted in a 6.7% (±1.2) improvement, and spreader graft placement also resulted in a consistent improvement of 2.6% (±13.5). Pressure within the main nasal cavity was consistently lower following butterfly graft placement versus a spreader graft or BNI. Butterfly and spreader graft placement also resulted in modest improvements in airflow allocation, whereas BNI demonstrated more variation (−1% to 12%). Heat flux was not significantly different; however, a small improvement in total heat flux was seen with all three interventions.

Conclusions: The results of this study demonstrate reduction in nasal airway resistance in all three surgical interventions, with the butterfly graft demonstrating superiority to the other two techniques. However, these data only reflect a static environment and not dynamic changes in airflow seen during respiration.

Key Words: Nasal valve collapse, internal nasal valve repair, butterfly graft, bioabsorbable nasal implant, spreader graft.

Level of Evidence: NA

INTRODUCTION

The ideal method or surgical technique for the repair of nasal valve compromise (NVC) remains elusive, and is the subject of much debate among rhinoplasty surgeons. Two systematic reviews of nasal valve repair (NVR) exhibit a multitude of level 4 evidence suggesting NVR approaches used in the repair of NVC, the spreader graft and the butterfly graft, using cadaveric specimens.5,6 In this prior study, we utilized computational fluid dynamics results in reduced nasal airflow resistance and improved patient satisfaction.1,2 However, due to the inherent surgical management of NVR, there is little higher-level evidence describing when intervention is necessary and which method is most appropriate. Given the volume of uncontrolled case series and other level 4 evidence, the American Academy of Otolaryngology–Head and Neck Surgery released a clinical consensus statement describing nasal valve compromise as a “distinct and primary cause of symptomatic nasal airway obstruction.”6 Despite a clinical consensus defining nasal valve compromise and its contribution to nasal airflow obstruction, to date there is no consensus on which surgical approach offers better patient outcomes.

Although nasal valve compromise can result from impairment in either the external or internal nasal valve (INV), the INV is most often the targeted region for intervention, as it forms the narrowest part of the nasal airway.3 Located at the junction of the caudal aspect of the upper lateral cartilage, septum, and caudal head of the inferior turbinate, small changes in this opening can generate exponential changes in nasal airflow.

Recently, our group compared two common surgical approaches used in the repair of NVC, the spreader graft and the butterfly graft, using cadaveric specimens.5,6 In this prior study, we utilized computational fluid dynamics...
(CFD), a modeling system based on anatomically accurate nasal airway models reconstructed from medical imaging modalities, to assess nasal airway resistance and heat flux (a measure of mucosal cooling) that are CFD biophysical variables strongly correlated with patient-reported symptoms.\(^7\)–\(^{10}\) We demonstrated that nasal airway resistance and heat flux were consistently improved in specimens that had butterfly graft placement, independent of the need for septoplasty or the order in which the surgical interventions were performed.\(^5\) Although this study aided in the identification of biophysical properties that can be assessed following surgical intervention, it was limited by both the number of cadaveric specimens that were used (thus limiting statistical analysis) and the fact that it only compared two of the most common surgical approaches to NVC (butterfly grafts and spreader grafts).

Although spreader grafts and variations thereof (placement of two cartilage grafts between the dorsal attachment of the upper lateral cartilages and the septum) are the current surgical standard for NVR (Fig. 1C),\(^{11}\) there has been increasing use of the butterfly graft (an onlay graft of conchal cartilage placed over the caudal septum and sutured to the caudal margins of the upper lateral cartilages)\(^4\) as a surgical alternative (Fig. 1B).\(^{12}–^{15}\) Recently, the use of a less invasive, bioabsorbable nasal implant (BNI) that is designed to reinforce the soft tissues adjacent to the upper and lower lateral cartilages has also been shown effective at improving the sensation of nasal patency, purportedly by stiffening the nasal sidewall (Fig. 1C).\(^{16,17}\)

In this study, we attempted to both validate and expand on our prior work by performing a three-armed study using single-surgical interventions on each cadaveric specimen. Each specimen was relegated to receiving a spreader graft, a butterfly graft, or the placement of a BNI, and our primary outcome was the overall change in nasal airway resistance postprocedure. As a secondary outcome, we attempted to discern whether changes in heat flux occurred following each intervention.

**MATERIALS AND METHODS**

This study used only human cadaveric tissue and therefore was exempt from prior review and approval by our institutional review board.

**Specimens and Surgical Procedures**

**Cadaveric dissections.** Nine fresh, thawed cadaver heads (ScienceCare, Phoenix, AZ) were obtained, and nasal cavities cleansed. Three specimens were assigned to each of the three separate intervention groups, and each specimen underwent a single treatment consisting of either spreader graft placement, butterfly graft placement, or insertion of bilateral BNIs (Fig. 2). Following this, each of the nine cadaver heads underwent external examination, and anterior rhinoscopy followed by cone beam computed tomography (CT) scan (Morita 3D Accuitomo 170; J. Morita, Osaka, Japan) prior to surgical intervention.

**Spreader graft placement.** Spreader grafts were placed via the standard external rhinoplasty approach utilizing transcolumellar and marginal incisions. The soft tissue envelope was then elevated deep to the superficial muscular aponeurotic system (SMAS) to the level of the rhinion, after which the plane was transitioned to a subperiosteal plane to the nasion. The upper lateral cartilages were sharply released from the dorsal septum. Spreader grafts were then sculpted from previously harvested septal cartilage from another specimen that had already undergone posttreatment CT scan. The same spreader

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**Fig. 1.** Diagram of surgical interventions. (A) The spreader graft technique separates the upper lateral (UL) cartilages from the nasal septum using harvested grafts (pink) to improve patency of the nasal airway. The lower lateral cartilages (orange) are not altered. The altered periseptal space is shown by the dashed line. (B) Butterfly grafts are on-lay grafts (pink). They are placed directly over the caudal septum and attach to the caudal border of the UL cartilage. The lower lateral cartilages are shown in orange for reference. (C) Bioabsorbable implants (pink) are anchored to the lower lateral cartilage (orange) inferior and medial and to the zygoma superior and lateral.
Pre-operative CT scan

$n = 9$ donors

Donor 1  Donor 2  Donor 3  Donor 4  Donor 5  Donor 6  Donor 7  Donor 8  Donor 9

Implantable bioanchor  Butterfly graft  Spreader graft

Repeat CT scan  Repeat CT scan  Repeat CT scan

Post-processing/CFD analysis  Post-processing/CFD analysis  Post-processing/CFD analysis

Fig. 2. Treatment algorithm. Each specimen underwent preoperative computed tomography (CT) scan followed by a specific intervention ($n = 3$ per treatment group) as depicted. CFD = computational fluid dynamics.

Grafts were used for each cadaver head. The spreader grafts were placed bilaterally and sutured between the septum and upper lateral cartilages using horizontal mattress 5-0 polydioxanone (PDS) sutures. The soft tissue envelope was then gently redraped and incisions were closed.

**Butterfly graft placement.** We began with harvesting of the conchal cartilage. A 3-cm curvilinear incision was made in the antihelical fold, and an anteriorly based flap was developed in a subperichondrial plane. A $2.5 \times 1.5$-cm cartilage graft was then harvested primarily from the concha cavum, preserving the posterior perichondrium. The conchal cartilage was then carved as previously described. Next, the graft was placed via an endonasal approach. A limited intercartilaginous incision was then made, and a subnasal SMAS plane was then developed to the level of the rhinion. The dorsal septum and upper lateral cartilage was then lowered to accommodate the graft. The caudal margin of the graft was secured to the caudal margin of the upper lateral cartilage at two points on each side using 5-0 PDS suture. The intercartilaginous incisions were then closed.

**Bioabsorbable nasal implant placement.** A marking pen was used to mark the scroll and nasal bone. The polymer implant was loaded into the delivery device. The nasal mucosa was incised immediately cephalad to the alar rim, and the delivery device cannula was advanced through the incision along the line drawn. Using the cannula, a dissection plane was created over the upper lateral cartilage. At the junction with the caudal aspect of the maxillary bone, the cannula was brought superficial to the bone. Using the 16-gauge cannula, a dissection plane was created above the periosteum on the superficial aspect of the maxilla. The cannula tip was advanced to the target marked 6 mm cranial to the bony/cartilaginous junction using palpation on the surface of the skin. The implant was delivered and the cannula withdrawn.

After each individual intervention, CT scans of the entire nasal cavity and external nasal soft tissue (0.33-mm pixels, 0.66-mm increments) were obtained.

**Modeling and Simulations**

**Digital reconstruction of nasal airways.** From the nine sets of pre- and postsurgical medical-grade scans (three sets each for the three surgical procedures—spreader graft, butterfly graft, and BNI), three-dimensional digital models of the corresponding nasal
airways were created using Mimics 18.0 (Materialise, Plymouth, MI). The reconstruction technique involved thresholding of the image radiodensity, at a typical delineation range of $-1024$ to $-300$ Hounsfield units. It is to be noted that the process additionally often involved cautious hand-editing of the scanned pixel domains, for an anatomically accurate rendering of the investigated airways.

Subsequently, the reconstructed models were meshed by segregating the airspace into tiny elemental volumes on the computer-aided design and meshing software ICEM-CFD 15.0 (ANSYS, Canonsburg, PA). As per established meshing protocols,5,18–21 the mesh in each model comprised approximately 4 million unstructured, graded, tetrahedral elements. We added a 2-cm-long outlet tube at the posterior end of the nasopharynx in each reconstruction to obtain a fully developed outlet flow. Unlike our previous study,5,18,19 the models did not segregate the left and right airways into two independent entities, so as to extract a comprehensive bilateral description of the nasal transport. This alleviated crossover airflow from one nasal airway to the other that arose from the decaying nasopharyngeal tissues that naturally occur in cadaveric specimens.

**Numerical simulations of the inhaled airflow and heat transfer.** We performed the nasal airflow and heat flux simulations on Fluent 14.5 (ANSYS) through a finite-volume approach, at a constant inlet-to-outlet pressure gradient of $-10$ Pa. Note that the nostrils served as the inlet in the simulated breathing, whereas the outlet was at the base of the 2-cm tube attached to the nasopharynx. Backed by prior evidence in the literature,8,22–24 for resting breathing, the simulations assumed a steady state laminar profile for the inspired airflow. The numerical scheme imposed the following boundary conditions: 1) no-slip (zero velocity) at the airway walls, which stood in for the internal nasal lining; and 2) an inlet pressure set to zero atmospheric pressure with the outlet pressure being fixed at $-10$ Pa. Other characteristic values for the flow domain included: air density, 1.204 kg/m$^3$; dynamic viscosity of air, $1.825 \times 10^{-5}$ kg/m·s; thermal conductivity of air, 0.0268 W/m·K; and specific heat of air, 1005.9 J/kg·K.7 The air temperature at the two nostrils was kept at 20°C, and the mucosal temperature at the internal tissue surface was 32.6°C.22,25

As part of postprocessing of the simulated breathing in the nasal models, we computed the bilaterial nasal airflow resistance (in Pa/L/min, considering the anatomic path from the nostrils through the choanae at the posterior end of the septum and into the nasopharynx), bilateral volumetric airflow (in mL/sec), airflow partitioning (the percentage of airflow that passes through either the left or the right nasal passage), and the surface heat flux along the airway tissue walls (in W/m$^2$). Of these, the nasal resistance is the ratio between the transnasal pressure drop to the volumetric airflow rate. Finally, the mean improvement factor is estimated as the ratio between the preoperative resistance to the postoperative resistance encountered by the nasal airflow.

Graphic visualization of the simulated flow parameters was prepared by importing the and analyzing the fluent-generated data on the FieldView 18.0 software package (Intelligent Light, Lyndhurst, NJ).
Statistical analysis. All statistical analyses described herein were performed using Kruskal-Wallis analysis of variance (ANOVA) in the statistical and graphical software PRISM version 8.0 (GraphPad, San Diego, CA). For improvement factor scores, mean data were calculated using pre/postoperative values. Given that values were continuous and calculated as a percent of change, compared between three independent groups, and each specimen was only used once, the Kruskal-Wallis ANOVA is indicated. All data are shown as individual data points, with bars representing group mean and error bars indicating SEM, unless otherwise indicated in the figure legends.

RESULTS
Nasal resistance was reduced with all three techniques. The greatest reduction occurred with the placement of a butterfly graft. This resulted in an overall drop in the inlet-to-outlet resistance (e.g., resistance from the nostrils to nasopharynx) of 24.9% (±7.3), 6.7% (±1.2), and 2.6% (±13.4) for butterfly grafts, BNI, and spreader grafts, respectively. This resulted in a mean improvement factor (the ratio of preoperative resistance to postoperative resistance) of 1.34 (±0.134) for butterfly grafts, 1.07 (±0.014) for the BNI, and 1.04 (±0.142) for spreader grafts (Fig. 3A). Pressure within the main nasal cavity was also consistently lower on the walls of the nasal airway (the flow resistance drops in pressure from the nostril inlet to the nasopharyngeal outlet) following placement of a butterfly graft versus a spreader graft or the insertion of a BNI (Fig. 3B).

We also calculated airflow partitioning (the net change toward a 50/50 distribution) as a result of each procedure as previously described.5 Placement of the BNI resulted in the widest range of variability with respect to airflow allocation (approximately −1% to 12%), whereas both butterfly and spreader graft placement resulted in modest, but consistent, improvements in airflow allocation (1.6% and 4.7%, respectively), though these improvements were not statistically significant (Fig. 4). The pre- and post-intervention values for the above CFD variables are shown in Table I.

Finally, we calculated the average change in heat flux following each intervention (Fig. 5). This biophysical variable, which correlates with the subjective sensation of nasal patency,7,9,26 was not significantly different among treatments; however, we observed small, consistent improvements

<table>
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<tr>
<th>Table I. Pre- and Postintervention CFD Variable Values.</th>
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<td>CFD Variable</td>
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<td>Preoperative pressure drop</td>
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<td>Preoperative SA, HF &gt; 50, m²</td>
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<td>Postoperative SA, HF &gt; 50, m²</td>
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BNI = bioabsorbable nasal implant; CFD = computational fluid dynamics; HF = heat flux; SA = surface area; SD = standard deviation.
in total heat flux with all three interventions (Fig. 5A). Furthermore, we also calculated the change in surface area of the main nasal cavity where heat flux was greater than 50 W/m² (Fig. 5B), but no significant differences between the treatments were noted.

DISCUSSION

NVC can be thought of as resulting from either one of two different causes, or both. The first being a static obstruction, whereas the second being dynamic collapse of the airway. Traditional surgical interventions aimed at correcting nasal obstruction were typically targeted at improving static obstruction. These interventions would include septoplasty, inferior turbinate reduction, and spreader grafts. Newer techniques, such as the butterfly graft (Fig. 1C), which has been clinically shown to improve both static obstruction and dynamic collapse, 15 and spreader flaps, combination spreader grafts (Fig. 1B) and batten grafts, combination of lateral crural strut grafts and batten grafts, flaring sutures and batten grafts, all have been developed to address both static and dynamic collapse in NVC. More recently, a BNI has been introduced as minimally invasive approach to prevent dynamic nasal sidewall collapse (Fig. 1C).

The search for the ideal surgical method for the treatment of NVC is ongoing, and certainly, with the wide variability in the exact anatomic cause, the patient motivations and expectations, and surgeon’s technical training and expertise, the choice for employment of a specific technique is complicated. As with all decision making in medicine, the choice should be heavily influenced by evidence-based medicine. To this end, our study attempts to compare three of the most common techniques (including a newly described and less invasive approach) using CFD analysis and parameters previously described by our group.

This is the first study to compare open repair techniques with a BNI. The BNI is minimally invasive and intended to add structural support to a weakened nasal sidewall. Our study serves as a proof-of-concept model for determining the effect this implant may have on heat flux and airway resistance using CFD analysis. As with the spreader graft and the butterfly graft, exact changes to nasal sidewall strength cannot be directly assessed with CFD. Thus, we determined the secondary effects on airway resistance and heat flux.

Heat flux and airway resistance have been shown previously to correlate with patient-reported outcome measures (PROMs) of subjective nasal patency. 9 Although this study was performed with cadaveric specimens, we see a modest improvement in overall heat flux and lower nasal airway resistance using the BNI (Figs. 3 and 4). Future work using CFD with patients following BNI insertion could further clarify the impact that BNI has on both objective measures (e.g., heat flux and nasal airflow resistance) as well as PROMs. 27,28

As previously demonstrated, the butterfly graft has more consistent reduction in nasal airway resistance than the spreader graft, and it is more effective in achieving equivalent airflow allocation between the right and left nasal airways. 5 This study confirms our prior findings, and demonstrates statistically significant improvement in nasal airway resistance following butterfly graft placement (Fig. 3). Furthermore, our data suggest that the butterfly graft is more consistent at improving nasal airflow allocation to the proper 50/50 distribution than either of the other two interventions (Fig. 4).
One of the major limitations of this study centers around the functionality of the BNI. This device is designed for the correction of nasal sidewall collapse. Therefore, it is unlikely to improve the nasal patency in this static model, and our results showing limited or only small effect on nasal airway resistance support the notion that a dynamic model may be necessary to more accurately evaluate this parameter following BNI placement; however, this model does serve to validate our initial work comparing spreader grafts to the butterfly graft. An additional limitation is the number of specimens used in this study. Although we have demonstrated significance differences in nasal airway resistance among our three interventions, we used only the minimal number of specimens necessary to perform statistical testing. Increasing our study numbers in the future may improve the results that we have shown while also increasing the confidence in these data. We also acknowledge the contribution of postmortem effects, such as mucosal decongestion, play in increasing the INV’s contribution to total nasal airway resistance. This could be addressed in future prospective studies where the dynamic changes in nasal airway could be directly assessed.

Future studies will use a method for data collection that will be able to detect movement of the nasal sidewall (e.g., dynamic nasal sidewall collapse) and will allow for objective comparison of various methods for correction of NVC. One such method is anatomic optical coherence tomography. A more comprehensive analysis using this imaging modality may be the key to improved comparisons between methods for correcting NVC.

CONCLUSION

This study contributes to the growing body of information attempting to provide objective evidence for improved nasal airflow following surgical manipulations of the internal nasal valve. Although BNIs have previously been shown to improve subjective nasal breathing on PROMs, we have shown only a small, but consistent improvement in the INV volume. Further work is required to determine the effect that BNIs and surgical techniques, such as the butterfly graft or spreader graft, have on dynamic changes in the internal nasal valve.

BIBLIOGRAPHY