Engineering Analysis of an Unreported Complication of Septoplasty

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Objectives: To describe a cause of recurrent nasal obstructive symptoms after septoplasties including the creation of a sizable submucous window and to suggest treatments for this complication.

Methods: Case report of a woman presenting with side-changing nasal dyspnea approximately 1 year after undergoing septoplasty and engineering analysis of nasal cavity airflow. We created a computer model of the airway, analyzed varying sizes of surgical defects, and optimized the geometry of the submucous window.

Results: An optimum area of resection to maximize the area of cartilage and/or bone resected and to minimize deflection of the septal area of iatrogenic litheness is a rectangular shape approximately 44 mm long by 12 mm high in our model.

Conclusions: A large submucous window can result in obstruction of nasal airflow after septoplasty owing to displacement of this compliant area with respiration under the forces described in the Bernoulli theorem. Treatment may include turbinate reduction and/or septal reconstruction.

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The primary investigator of this study (C.G.) has observed a small group of patients with a previously undescribed complication resulting from the creation of a submucous window (SMW) during septoplasty. These patients, who presented with symptoms of side-changing nasal obstruction after septoplasty, were found to have a highly compliant segment of the septum corresponding to an area of resected bone and cartilage. This area corresponds to the mucosa overlying the SMW. The SMW resection was described as far back as 1905 by Killian1 (Figure 1). This nonrigid (easily flexible) area of septum will be referred to as the septal area of iatrogenic litheness (SAIL). This acronym is intentionally chosen to emphasize the behavior of this area, which is like the sail of a boat that bows under the force of the wind.

On inspiration, deformation of the SAIL was observed toward one side of the nasal airway or the other, depending on which turbinate happened to be more engorged, under the forces described in Bernoulli’s theorem, which states that an increase in the speed of a fluid (or air, in this case) occurs simultaneously with a decrease in pressure.2 This resulted in narrowing of the nasal airway on that side. Symptoms were relieved clinically by supporting the SAIL in the midline with a cotton tip applicator.

We believe that this phenomenon may be a common yet previously unrecognized cause of recurrent nasal obstructive symptoms after septoplasties that include the creation of a sizable SMW. We herein include photographic and video footage of the phenomenon to report a case. In addition, we use advanced engineering methods to analyze a computer model of a post-SMW nasal airway to demonstrate it. We then analyze various sizes of surgical defects to determine their corresponding degree of deflection and calculate the optimal (largest-size resection with minimal deflection of the SAIL) SMW geometry in this model. This sequence of actions is performed to guide surgical judgment when an SMW is necessary, such as when harvesting cartilage. Finally, we discuss suggested treatments for this complication.

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approximately 1 year after undergoing septoplasty by another surgeon. The patient indicated that her nasal breathing had initially improved before symptoms returned. She was otherwise healthy and had no other symptoms of rhinitis. Operative notes revealed that a classic submucous resection of septal bone and cartilage had been performed, leaving a submucoperichondrial/mucoperiosteal bony-cartilaginous defect (ie, an SMW).

On examination, the intact, well-healed, septal mucoperichondrial/mucoperiosteal tissue overlying the bony-cartilaginous window (the SAIL) was noted to deviate to the side opposite the most engorged inferior turbinate on inspiration (Figure 2; a short video is available at http://www.archfacial.com). Serial examinations revealed that the direction of septal deflection was side changing and contralateral to the most enlarged inferior turbinate. Support of the SAIL in the midline with a cotton-tip applicator immediately relieved symptoms.

A stepwise approach was planned, consisting of turbinate reduction followed by delayed reconstruction of the SMW if the turbinate reduction did not relieve symptoms. A submucous resection of the inferior turbinates was performed. At 3 postoperative months, the patient continued to report relief of symptoms, and no further treatment was required.

**METHODS**

**NASAL CAVITY AIRFLOW ANALYSIS**

We obtained 1.5-mm axial computerized tomographic images (using a Somatome Sensation Multislice device; Siemens Medical Solutions, Malvern, Pennsylvania) of the skull of an 18-year old white man who had an asymmetric nasal airway. The patient was chosen because the asymmetry of the flow channels was expected to create skewed flow regions like those expected of patients with asymmetric swelling of the inferior turbinates, as is commonly seen during the nasal cycle. In addition, the model is designed as a proof of concept; therefore, the often realistic scenario of an imperfectly symmetric nasal airway was necessary. The skewed flow regions are hypothesized to create a significant pressure differential between the left and right flow regions of the nasal cavity. The computed tomographic data were imported into commercially available software in image format (Mimics, version 11.11; Materialise, Ann Arbor, Michigan). The processing software can create solid 3-dimensional entities using segmentation of grayscale values within 2-dimensional images. Editing functions were used to crop the nasal cavity from the rest of the skull. Figure 3 shows an axial image from the set used in this study. We imported initial graphics exchange specification line contours from the images into engineering design analysis software (ANSYS; ANSYS Inc, Canonsburg, Pennsylvania), representing the entities created for flow regions of the nasal cavity. The surface areas of the model were created in ANSYS using the contour lines as a guide, a process called skinning. Last, volumes were created from the outer surface areas.

Steady airflow was simulated through the nasal cavity. Air was modeled as Newtonian and incompressible using properties from the ANSYS library. Temperature effects were not included in the analysis. The boundary conditions simulated the airflow at a moderate “sniffing” flow rate by using a pressure drop of 160 Pa between the nares and the throat.

The entire nasal cavity volume was meshed with Fluid 142 3-dimensional elements available in ANSYS. Local element sizing was used along the septum walls to ensure the convergence of solutions and eliminate calculation errors. For verification, the number of nodes on the wall was doubled until there was a convergence of solutions. The final mesh of the nasal cavity shown in Figure 5 consists of 113 721 elements and 24 804 nodes.

The governing equations are the incompressible, unsteady Navier-Stokes equations. We used ANSYS FLOTTRAN to formulate the equations and determine the solution. For an in-
compressible Newtonian fluid, in the absence of body forces, the momentum equation is represented as

\[ \rho \frac{\partial u}{\partial t} + u \cdot \nabla u = -\nabla p + \mu \nabla^2 u \]

and the incompressibility is expressed as

\[ \nabla \cdot u = 0, \]

where \( u \) is the velocity vector, \( \rho \) is the density, \( p \) is the pressure, \( \mu \) is the kinematic viscosity, and \( \nabla \) is the vector field whose components are the partial derivatives of the function. The SIMPLEF algorithm of the ANSYS software is used to uncouple the solution variables and obtain the final solution. For more information on the solution method, consult the documentation for ANSYS, version 11.0.4

SEPTUM DEFLECTION ANALYSIS

A solid model was created to simulate the SAIL with a shape and size similar to that described by Killian. The section was approximated as a thin area with the dimensions given in Figure 6. These dimensions were chosen to represent the SMW of a septoplasty that preserves 1-cm caudal and dorsal struts. The area was meshed with 1300 Shell 181 elements (ANSYS Finite Elements; ANSYS Inc, Canonsburg, Pennsylvania). Average pressure values were obtained from the nasal airflow analysis and subsequently applied as a pressure differential boundary condition along the solid model representing the SAIL. The outer edges of the model were restricted from movement in all directions. The wall was defined as having the hyperelastic material properties of vein, given its large role in the material makeup of the mucoparichondrium. A 3-parameter Mooney model using hyperelastic material was defined in ANSYS. The parameter values were calculated using experimental data presented by Fung. Figure 7 shows the calculated parameters and the model curve projected onto the experimental data. Multiple time substepping was automatically enabled in ANSYS to the extent that the solution ensured convergence. The large displacement solution option was enabled in the calculation because large displacements were expected. The model was solved...
for walls of thickness of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 mm. Using the 2-mm wall thickness model as a base, the model was further modified to consider the effect of reducing the SMW length by as much as 40% from the posterior edge, which would correspond approximately to the bony-cartilaginous junction. At this reduced length of SMW, the height of the SMW area was also reduced by as much as 40% from its top edge. Results for peak displacement values of the resected area were taken for different wall thicknesses and at different reductions of the length and height.

Last, we wrote an optimization function to determine the ideal ratio to reduce the length and the height of the SMW to minimize displacement of the SAIL. A script file was parametrically written for the entire analysis and iterated using the subproblem optimization method with a maximum of 40 iterations. For more information on this method, the reader is advised to consult the documentation accompanying ANSYS, version 11.0.4 The optimization function sought to minimize the reduction of the resection (ie, allow the largest possible resection) while also minimizing the maximum displacement of the SAIL. For the optimization, the length and the height were allowed to be reduced by as much as 50% of their initial values. The objective of the optimization was to zoom in on the combination of SAIL length and height that would minimize reduction of the SAIL such that the maximum displacement of the SAIL is within 0.3 mm. This value was conveniently chosen because it is 20% of the narrowest airway width in the model. Simply reducing the length and height unilaterally does not account for the interaction between the 2 variables because the displacements are expected to be highly nonlinear. The optimization can account for the interplay between variables and determine the ideal reduction of each variable required to minimize SAIL deflection.

**RESULTS**

Figure 8A shows the velocity contours in the coronal plane in the nasal valve region. The highest airflow velocities were found in this region, with most of the peak flow contained within a range of 10 to 40 m/s. These numbers are in the region of those reported by Zhao et al.5 The asymmetry of the cavity has clearly created a difference in velocity profiles among the 2 sides with significantly more flow volume and velocity in the left cavity. A reduced flow area over a section of the right cavity has limited the amount of flow on that entire side. Figure 8B shows the velocity contours in a parasagittal plane, exposing the flow through the left cavity. The contours de-
scribe higher velocities in the nasal valve region and in the region superior to the inferior turbinates.

Figure 9 shows the pressure contours of the left nasal cavity along the septum wall in engineering design analysis software (ANSYS; ANSYS Inc, Canonsburg, Pennsylvania). Values in the color contour bar are expressed as meters per second.

Figure 10. Deformed displacement contours in the septal area of iatrogenic litteness in engineering design analysis software (ANSYS; ANSYS Inc, Canonsburg, Pennsylvania). Values in the color contour bar are expressed as meters per second.

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Figure 9 shows the pressure contours of the left nasal cavity along the septum. The contours describe highly variable pressure over small sections of the nasal valve region, with a consistent pressure contour over the rest of the septum wall. The SAIL was approximated to the SMW in the diagram by Killian1 (Figure 1), and all nodal pressure values were recorded. These values were averaged for both sides of the cavity and determined to be −51 Pa for the right side and −142 Pa for the left side. This pressure differential was subsequently applied as a boundary condition to the SAIL model.

Figure 10 shows the total displacement in the 2-mm-thick SAIL wall. The most pertinent measure to consider is the peak displacement in the SAIL because a large displacement will cause intrusion into the airway and reduce its cross-sectional area. The peak displacement in the 2-mm-thick model is 0.97 mm. Figure 11 shows the peak displacement of the wall as the wall thickness is increased from 1.0 to 3.5 mm (for the SAIL dimensions in Figure 6). Different mucosal thicknesses in such a range are found in various locations along the septum, and Figure 11 describes diminishing returns as the thickness is increased past 2.5 mm. Figure 12 shows the peak displacement as the length of the resected wall section is reduced by as much as 40% of its original length (here, the thickness used was 2 mm and the height was 18.75 mm). The data are nonlinear with an increasingly stronger decrease in displacement as the reduction of the length is continued. Figure 13 shows the effect on wall displacement as the height of the resection is reduced from its top edge (thickness, 2 mm; length, 26.7 mm). The analysis was performed on the model with SAIL length spanning from approximately the bony-cartilaginous junction to the posterior edge of a 1-cm caudal strut, which is a 40% reduction in length. Figure 13 describes a relatively linear correlation.

Figure 14 is a bubble chart showing the size of the SAIL as the size of each bubble plotted according to the length and height of the SAIL. The larger the bubble, the bigger the SAIL area is. The solution determined the larg-
Submucous resection during septoplasty is a common maneuver described in detail as far back as 1905 by Kilian; the basic maneuvers are still considered valid. Septoplasty patients have suboptimal outcomes approximately 15% to 37% of the time. Reasons for failure are probably numerous and could include untreated rhinitis, turbinate hypertrophy, overresection of the turbinates, internal or external nasal valve collapse, and persistent or recurrent nasal septal deviation. As with any surgery, accurate preoperative diagnosis can eliminate many of these instances by carefully tailoring treatments to specific causes.

One cause for the postseptoplasty nasal obstruction that the primary author has observed in 3 patients is dynamic displacement of the nasal septum overlying an SMW. On clinical examination, a SAIL is seen bowing into the airway on inspiration. It is observed returning to the midline on cessation of airflow. A small instrument such as a cotton tip applicator can be used to support this region in the midline. This maneuver results in relief of nasal obstructive symptoms with inspiration and is diagnostic.

Although many, if not most, surgeons consider it prudent to be as conservative as possible with the amount of resected bone and cartilage, classical teaching specifies that while a minimum of a 1.0 to 1.5 cm of caudal and dorsal strut of cartilage are maintained, the surgeon is free to remove as much cartilaginous and bony septum as necessary to correct the deviation. The concern in the literature safeguarded by this stipulation is that the external nose requires these struts to maintain adequate vertical support and to prevent its collapse.

Various other septoplasty maneuvers have been discussed in the literature, including scoring, suturing, and other techniques to reshape curved cartilage, repositioning, and even replacement of deviated areas. These are designed to maintain the septum in the midline with more conservative resection of tissue than a classic SMW. However, this can be difficult to maintain owing to the tendency of cartilage to distort back to its original shape.

Today septoplasty is often a combination of some degree of SMW and these other techniques; however, there is still often some degree of submucous resection.

In addition, surgeons often harvest cartilage and/or bone from the nasal septum for use in other areas, thus creating an often sizable SMW. Optimization of SAIL geometry to minimize its size vs displacement was performed as a suggested guideline. Although this routine considered a rectangular SAIL, the suggested ratio of length to width is probably more important than the exact shape. These dimensions could be useful to consider when removing cartilage from the septum for any reason. The location of the SAIL probably also is significant. As can be observed in Figure 8B, there is a high-velocity stream anterior and superior to the inferior turbinate that affects the pressure in these areas along the septum. Therefore, avoiding a SAIL in these areas would be favorable.

Nasal surgeons are very familiar with Bernoulli’s theorem; it is commonly discussed with regard to the internal nasal valve. In this area, its effects can often be easily appreciated clinically by a visible collapse of the nasal sidewall on inspiration. Diagnosis of this phenomenon as a cause of nasal obstruction can be confirmed by supporting this area during breathing with a report of relief of symptoms by the patient. Although Bernoulli’s theorem describes a cylindrical flow channel, which is perhaps a somewhat crude approximation of the complex geometry of the nasal airway, its application to the nose can give basic, clinically useful predictions. At a SAIL displacement of 0.97 mm, the flow channel is reduced at its minimum point from 1.70 to 0.73 mm. Using the relationship from Poiseuille’s equa-

![Figure 13. Peak septal area of iatrogenic litheness displacement as the height of the submucous window (SMW) is reduced by as much as 40% of its original height. The analysis was performed with the reduced length of 40%.](https://archfaci.jamanetwork.com/)

![Figure 14. Septal area of iatrogenic litheness (SAIL) area optimization iterations. The 8 iterations of the optimization analysis are shown as data points on the bubble chart. The relative total area of the SAIL (the size of each bubble) is plotted according to the length and height of the SAIL. F indicates feasible bubbles; and I, infeasible bubbles; *, the optimized feasible solution.](https://archfaci.jamanetwork.com/)

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tion that $R = \frac{1}{r^4}$, where $R$ indicates resistance and $r$ is the radius, this multiplies the resistance by almost 30 times, which would be noticeable to the patient. Obviously, any reduction in the size of SAIL displacement would have a large effect on flow.

The nasal valve is commonly described as a triangle that includes the nasal sidewall, the inferior turbinate, and the nasal septum. Normally the nasal sidewall is compliant and collapsible, whereas the other 2 elements of this relationship are essentially rigid. However, after a large SMW is created during septoplasty, the septum becomes compliant in the resected area as well. Once this occurs, this area is subject to the dynamic deforming forces of flowing air just like the nasal sidewall, that is, it becomes subject to the forces described in Bernoulli’s theorem.

Deformation under this effect probably occurs to some degree when any cartilage or bone is removed. However, the displacement appears to become more sizable as the surface area of the resection increases. Once the septum is displaced into the airway far enough, the patient will begin to notice airflow obstruction. Correlation of the model to the original computed tomographic scans shows that in the high displacement region of the SAIL, the wider (ipsilateral) nasal vault is only 1.7 mm at some points. This indicates that the cross-sectional area of the nasal flow channel is reduced by more than 50% in some regions in the case of a 2-mm SAIL wall, and that the channel could be completely cut off at some points in the case of a 1-mm-thick SAIL wall. This is important because the septum wall varies considerably in thickness in different areas.

Furthermore, as this deflection repeatedly occurs and pressure is repeatedly applied to the SAIL tissue, we theorize that the phenomenon of biological creep may actually increase the laxity of this segment, making the problem a progressive one. This may explain why observed patients reported that their surgery was initially successful, but symptoms later returned. Another explanation may be maturation of intermucoperichondrial scar tissue, which softens after an initial period of stiffness. Surgical edema may also cause some stiffness before slowly receding. If scar tissue can stiffen the SAIL, prevention of early SAIL mobilization with postoperative septal splints may be prophylactic.

This model describes a static deformation rather than the dynamic one seen clinically because the authors are concerned with analyzing the magnitude of the deformation of the SAIL at peak flow and not necessarily the time progression of that deformation. In addition, this makes the flow conditions consistent with those in other recent work. Future work will include the time progression of SAIL deformation over the entirety of a single breath.

Ideally, the septum would be straight and midline, and the nasal cavities would be mirror images of one another. With such geometry, no deformation of the SAIL would be expected no matter how compliant it was because the forces on either side would offset one another. However, in reality the septum is seldom perfectly straight and the nasal cavities are not enantiomers. More significantly, the nasal cycle continues to asymmetrically govern airflow over time with alternating engorgement of the turbinates. This results in asymmetric pressures in the nasal passages resulting from asymmetric airflow. The authors hypothesize that for this reason, all observed patients reported some degree of alternating obstruction similar to that often seen in inferior turbinate hypertrophy.

Bernoulli’s theorem describes decreasing pressure associated with increasing flow rate. The SAIL is therefore expected to deviate toward the most patent side. Hence, the patient is expected to have relative obstruction on the side of turbinate engorgement, as always, and on the contralateral side from deflection of the SAIL into the airway. In addition, energy losses of the airflow will result from the sudden expansion of an internal flow channel (such as the nasal cavity on the side opposite the direction of SAIL deviation) because turbulent flow and recirculation can have an effect on the local flow field. Therefore, the nasal obstruction, while asymmetric in severity, can be bilateral.

Of the 3 patients identified, one was treated. She underwent submucosal resection of the inferior turbinates, which resulted in full relief of symptoms as of 3 postoperative months. The mechanism of treatment is thought to be less dynamic turbinates and enough room in each nasal vault that the maximal degree of septal displacement cannot significantly fill the expanded space within it. It is unknown how long this success will last. Nonsurgical management could include saline spray to moisten the SAIL-air interface, thereby reducing energy loss owing to friction between air and mucosa. Another theoretical option for treatment would be surgical reconstruction of part or the entire SMW defect to restore rigidity such as replacement of appropriately trimmed bone, cartilage, or acellular dermis graft material (eg, Alloderm; LifeCell Corporation, Woodlands, Texas) between the carefully separated mucosal flaps.

Certainly such dimensions as the cross-sectional dimensions of the nasal cavity at different levels and on different sides, the dynamic sizes of the turbinates, and the thickness and stiffness of the mucoperichondrium for any given individual fall along a spectrum arising from the vast diversity of humankind. Variations in the degree of sepal deflection and degree of nasal obstruction are expected because these and other variables that influence this phenomenon vary over time and from one individual to the next. This study does not attempt to account for all these possible variances. Rather, its purpose and relevance is primarily in demonstrating an important concept and suggesting guidelines for harvesting septal cartilage and/or bone when necessary.

CONCLUSIONS

A clinical example and engineering analysis demonstrate that the creation of a submucous cartilaginous and/or bony window during septoplasty can result in a compliant area of the nasal septum. This area can deform under the forces described in Bernoulli’s theorem to the degree that significant obstruction of airflow can occur. Displacement is related to the size of the defect and to mucosal thickness. Surgeons should be wary of this potential complication during surgery and evaluate it clinically in patients undergoing septoplasty who...
have symptoms of persistent or recurrent obstruction. For surgical guidance when an SMW is necessary, such as when harvesting cartilage or bone for use elsewhere, an optimum area of resection to maximize the area of cartilage and/or bone resected and minimize SAIL deflection is a rectangular shape approximately 44 mm long by 12 mm high in our model. In patients found to have this complication, treatment may include turbinate resection and/or septal reconstruction.

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