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The relationship between nasal resistance to airflow and the airspace minimal cross-sectional area

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Abstract

The relationship between nasal resistance (R) and airspace minimal cross-sectional area (mCSA) remains unclear. After the introduction of acoustic rhinometry, many otolaryngologists believed that mCSA measurements would correlate with subjective perception of nasal airway obstruction (NAO), and thus could provide an objective measure of nasal patency to guide therapy. However, multiple studies reported a low correlation between mCSA and subjective nasal patency, and between mCSA and R. This apparent lack of correlation between nasal form and function has been a long-standing enigma in the field of rhinology. Here we propose that nasal resistance is described by the Bernoulli Obstruction Theory. This theory predicts two flow regimes. For $mCSA > A_{crit}$, the constriction is not too severe and there is not a tight coupling between R and mCSA. In contrast, when $mCSA < A_{crit}$, nasal resistance is dominated by the severe constriction and it is predicted to be inversely proportional to the minimal cross-sectional area ($R \propto mCSA^{-1}$). To test this hypothesis, computational fluid dynamics (CFD) simulations were run in 3-dimensional models based on computed tomography scans of 15 NAO patients pre- and post-surgery (i.e., 60 unilateral nasal cavities). Airspace cross-sectional areas were quantified perpendicular to airflow streamlines. Our computational results are consistent with the theory. Given that in most people $mCSA > A_{crit}$ (estimated to be 0.37 cm^2), this theory suggests that airway constrictions are rarely an exclusive contributor to nasal resistance, which may explain the weak correlation between mCSA and subjective nasal patency.

Keywords

nasal resistance; acoustic rhinometry; orifice flow; computational fluid dynamics (CFD) simulations; computational streamline rhinometry

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INTRODUCTION

The interplay between nasal form and function remains unclear, particularly in the context of nasal airway obstruction (NAO). Acoustic rhinometry has been extensively used in vivo to measure the cross-sectional areas of the nasal airspace as a function of distance from nostrils. The technique has many strengths - it is non-invasive, quick to perform, requires little patient cooperation, and does not involve radiation exposure. After acoustic rhinometry was introduced (Hilberg et al., 1989), there was much optimism that it would lead to improved health outcomes for NAO patients (Grymer, 1995; Grymer et al., 1993; Roithmann et al., 1994). The expectation was that knowledge of the severity and location of airway constrictions would provide objective criteria for selecting patients who may benefit from nasal surgery. Unfortunately, subsequent studies found a low correlation between the airspace minimal cross-sectional area and subjective scores of nasal patency (Andre et al., 2009). Today the benefit of using acoustic rhinometry for clinical decisions remains controversial (Barnes et al., 2010; Eccles et al., 2010). The goal of this manuscript is to systematically investigate the relationship between the airspace minimal cross-sectional area and nasal resistance to airflow.

One central assumption for using acoustic rhinometry as a diagnostic tool is the hypothesis that nasal resistance is strongly correlated to the airspace minimal cross-sectional area (mCSA). This hypothesis has been tested in several in vivo studies. Except for one study that reported a strong correlation between mCSA and nasal resistance (Roithmann et al., 1994), all other studies found either a moderate correlation between these variables (typically Pearson $|r| = 0.4$ to 0.6) (Scadding et al., 1994; Tai et al., 1998; Wandalsen et al., 2012; Yepes-Nunez et al., 2013), or no correlation at all (Naito et al., 2001; Numminen et al., 2002; Passali et al., 2000; Zhao et al., 2014). To the best of our knowledge, a systematic investigation of the relationship between nasal resistance and mCSA has not been performed. In vivo studies are clouded by the possibility of experimental error. Accurate measurements of nasal resistance via rhinomanometry require a skilled operator and patient cooperation (Carney et al., 2000; Clement and Gordts, 2005; Cole, 1989). Acoustic rhinometry measurements are also affected by several factors, including sound leakage at the nostril, the position of the sound tube, and inconsistency in user operation (Chandra et al., 2009; Clement and Gordts, 2005; Fisher et al., 1995). Another limitation of acoustic rhinometry is that it over-estimates cross-sectional areas in the posterior nose due to sound leakage into the sinuses (Tarhan et al., 2005). These sources of experimental error raise the possibility that the low correlation between nasal resistance and mCSA observed in in vivo studies reflects the difficulty of performing in vivo measurements rather than lack of an inherent relationship between these two variables.

This manuscript introduces a new theoretical framework for understanding the relationship between nasal resistance (R) and the airspace minimal cross-sectional area (mCSA). We propose that nasal resistance is described by the Bernoulli Obstruction Theory, which predicts a strong correlation between R and mCSA, but only for severe constrictions where mCSA is smaller than a critical area A_{crit} . In addition, a novel method is introduced to quantify cross-sectional areas of the nasal airspace based on computational fluid dynamics (CFD) simulations. While acoustic rhinometry evaluates the cross-sectional areas

perpendicular to the acoustic path, our method quantifies the cross-sectional areas perpendicular to airflow streamlines, which is arguably a more physiological approach. The method is used to investigate the relationship between mCSA and nasal resistance in 15 patients before and after nasal surgery. Our results are discussed alongside a comprehensive literature review on this topic and support the hypothesis that nasal resistance is described by the Bernoulli Obstruction Theory.

METHODS

Patient Cohort

This study was approved by the IRB committee at the Medical College of Wisconsin and informed consent was obtained from each patient. Fifteen adult patients undergoing NAO surgery (septoplasty, turbinectomy, and/or nasal valve surgery - i.e. functional rhinoplasty) were recruited (Table S1, Supplementary Material). Only NAO patients whose symptoms were due to structural abnormalities (septal deviation, inferior turbinate hypertrophy, or nasal valve collapse) were included. Patients with a history of previous nasal surgery and/or nasal obstruction symptoms due to non-structural causes (e.g., sinusitis) were excluded. The cohort included 12 males and 3 females all of Caucasian ethnicity with an average age of 35 ± 9 years. Pre- and post-operative axial CT scans were obtained with 0.6-mm thickness and in-plane resolution of 0.31 mm. The post-operative scan was acquired 3 to 6 months after surgery. Noses were not decongested prior to scanning because our goal was to study nasal physiology in its natural state.

Subjective scores of nasal patency

Patients completed the Nasal Obstruction Symptom Evaluation (NOSE) questionnaire to collect information on patient-reported symptoms before and after surgery. The NOSE scale is a disease-specific quality-of-life instrument for NAO used to measure surgical success (Rhee et al., 2014; Stewart et al., 2004b; Stewart et al., 2004a). It is a five item scale in which patients score, over the past month, their symptoms of nasal congestion, nasal blockage, trouble breathing through the nose, trouble sleeping, and difficulty breathing while exercising on a scale ranging from 0 (not a problem) to 4 (severe problem). These numbers are summed and multiplied by 5 to give a score ranging from 0 (no symptoms) to 100 (severe symptoms). Patients also used a unilateral visual analog scale (VAS) to rate their sensation of nasal airflow before and after surgery. Patients were asked to cover one nostril and rate their ability to breathe through the uncovered nostril on a scale of 1 (completely obstructed) to 10 (air flowing freely through nostril). For each patient, the left and right cavities were assigned as the most obstructed or least obstructed cavity based on the pre-surgery VAS scores.

CFD simulations

Three-dimensional models of the nasal anatomy were built from the CT scans in Mimics 16.0 (Materialise, Leuven, Belgium) using a Hounsfield range of -1024 to -300 units to segment the airspace. The paranasal sinuses were excluded from the anatomy under the assumption that they have a minimal effect on the airflow patterns in the main cavity. All models were oriented with the Z-axis in the anterior-posterior direction, the Y-axis in the

inferior-superior direction, and the X-axis in the lateral direction. Tetrahedral meshes with approximately 4 million cells were created in ICEM-CFD 14.0 (ANSYS, Inc., Canonsburg, PA). All tetrahedral cells had quality > 0.3 to avoid highly distorted elements.

Steady-state, laminar, inspiratory airflow simulations were conducted in Fluent 14.0 (ANSYS, Inc.) with the following boundary conditions: (1) inlet pressure at the nostrils = 0 Pa, (2) no slip at the walls, and (3) outlet pressure set to a constant value such that a 19 Pascal pressure drop $\Delta p = 19$ Pa was adopted because on average it resulted in a bilateral airflow of 250 ml/s in post-operative NAO patients, which is the inspiratory rate in adults breathing at rest (I.C.R.P., 1994). The outlet pressure p_{outlet} required to obtain $p_{\text{choana}} = -19$ Pa at the nasal choana was estimated by running preliminary simulations to fit the constants k_1 and k_2 in the power law equation $p_{\text{choana}} = k_1(p_{\text{outlet}})^{k_2}$. Nasal resistance ($R = \Delta p / Q_v$) was defined as the ratio of the transnasal pressure drop $\Delta p = 19$ Pa (nostrils to choanae) to the volumetric airflow rate Q_v .

Computational Streamline Rhinometry

Cross-sectional areas of the nasal airspace were computed perpendicular to flow streamlines (Figure 1). The method, dubbed Computational Streamline Rhinometry (see Supplementary Material for details), represents one strategy to compute cross-sectional areas of the nasal cavity. It is expected to provide results similar to previously described methods based on geometric centerlines (Tarhan et al., 2005; Terheyden et al., 2000). Area-distance curves were computed for 10 streamlines for each nasal cavity (Figure 2). To compute an average area-distance curve, the distance along each streamline had to be normalized, given that each streamline had a different length. The normalized distance from nostrils D was defined so that $D=0$ corresponded to the nostril and $D=1$ corresponded to a coronal plane at the end of the septum (choana).

The mCSA for each cavity was defined as the smallest mCSA among all 10 streamlines studied per cavity. To evaluate whether future studies can select a single streamline representative of nasal airflow, as opposed to the more labor-intensive method of selecting the smallest mCSA among 10 streamlines, the variability of the mCSA among the 10 streamlines was quantified via the coefficient of variation $C_v = \sigma/\mu$, where σ is the standard deviation and μ is the mean. A histogram of the coefficient of variation demonstrated that there was relatively little variation in the mCSA for different flow streamlines (Figure S3, Supplementary Material). The coefficient of variation was 4.6% on average and less than 10% in the majority of nasal cavities studied.

Bernoulli Obstruction Theory

We propose that the relationship between nasal resistance and airspace minimal cross-sectional area can be described by the Bernoulli Obstruction Theory (also known as orifice flow), which is derived as follows. Consider a cylindrical tube of diameter D with a constriction where the tube diameter is reduced to d (Figure S1, Supplementary Material). The Bernoulli and continuity equations for steady frictionless incompressible flow imply that

$$Q = A_1 V_1 = A_2 V_2 \quad (1)$$

$$p_1 + \frac{1}{2} \rho V_1^2 = p_2 + \frac{1}{2} \rho V_2^2 \quad (2)$$

where A is cross-sectional area, V is air velocity, ρ is air density, p is air pressure, and the indices 1 and 2 refer, respectively, to two positions along a streamline, one upstream from the constriction and one at the center of the constriction (Figure S1, Supplementary Material). Solving for V_2 and substituting the result back into the continuity equation, one finds the orifice flow equation (White, 2008)

$$Q = C_d A \sqrt{\frac{2 \Delta p}{\rho (1 - \beta^4)}} \quad (3)$$

where $p = p_1 - p_2$ is the pressure gradient, A is the cross-sectional area at the constriction, and $\beta = d/D$ is the ratio of the constriction diameter to the tube diameter. The dimensionless discharge coefficient C_d is introduced as a correction for the approximations made, namely (a) the Bernoulli equation is exact only for an ideal fluid (zero viscosity), and (b) experiments demonstrate that the diameter determining the pressure drop is not the constriction diameter itself, but rather the diameter of the fluid jet exiting the constriction (White, 2008). The orifice flow equation is used in many flowmeters to convert pressure measurements into flowrates. The coefficient $C_d = f(\beta, Re)$ is a function of the Reynolds number Re and the ratio β , and must be obtained via experimental measurements. Its value depends on the particular design of the obstruction, but typically ranges from 0.6 to 1.0 for flowmeter designs with $0.25 < \beta < 0.75$ and $10^4 < 10^7$ (Cengel and Cimbala, 2006; White, 2008).

Here we propose that the relationship between nasal resistance and the airspace minimal cross-sectional area obeys the orifice flow equation when the constriction is severe enough that the resistance of the constricted segment overshadows the resistance of all other regions of the nasal cavity. In this flow regime ($mCSA < A_{crit}$, where A_{crit} is a critical area), unilateral nasal resistance obeys the relationship

$$R = \frac{\Delta p}{Q} = \frac{1}{C_d} \left(\frac{\rho \Delta p}{2} \right)^{\frac{1}{2}} \frac{1}{mCSA} \quad (4)$$

where the equation was simplified under the assumption of severe constrictions ($\beta \rightarrow 0$), so that $\lim_{\beta \rightarrow 0} (1 - \beta^4) = 1$. Assuming that the coefficient C_d is roughly constant in nasal cavities of different individuals and measuring nasal resistance at a constant pressure drop ($p = \text{constant}$), this equation predicts that nasal resistance is inversely proportional to the airspace minimal cross-sectional area, namely $R \propto (mCSA)^{-1}$. To test this hypothesis, a power law was used to fit the relationship between nasal resistance and airspace minimal cross-sectional area, namely

$$R=a(mCSA)^b \quad (5)$$

where a and b are fitting constants.

A key assumption when applying equation (4) to describe nasal airflow is that a single constriction contributes disproportionately to nasal resistance. In flowmeters, where the orifice flow equation is often used to describe the pressure-flow relationship, the tube diameter is constant upstream and downstream of the constriction, and the constriction is limited to one narrow segment. In contrast, a localized constriction is not always the cause of nasal obstruction in NAO patients. For example, patients with inferior turbinate hypertrophy have nasal airways that are narrower throughout the turbinate region. Therefore, a strong coupling between R and $mCSA$ should be expected only when the airway constriction is so severe that it overshadows the resistance of other regions of the nose. Thus, the question is: how severe a constriction needs to be to become the main determinant of nasal resistance? Here, we arbitrarily define a critical area (A_{crit}) as the $mCSA$ value required to elevate nasal resistance above the healthy range. In healthy individuals, unilateral nasal resistance is 0.138 ± 0.044 Pa.s/ml (Zhao and Jiang, 2014). Assuming that nasal resistance has a Gaussian distribution, one expects that 95% of healthy individuals have unilateral resistance within two standard deviations of the mean, which means $R < 0.23$ Pa.s/ml in healthy subjects. Substituting $R_{crit} = 0.23$ Pa.s/ml into equation (5), the critical area below which airway constrictions are predicted to elevate nasal resistance beyond the healthy range can be estimated as $A_{crit} = (R_{crit}/a)^{1/b}$. (Note that the criterion $mCSA < A_{crit}$ does not necessarily imply that resistance is restricted to a single constriction. Nevertheless, this criterion does imply (a) the presence of a constriction and (b) that nasal resistance is elevated above the healthy range.)

Statistical Analysis

Two-tailed paired Student's t-tests were used to test the hypothesis that post-operative values were statistically different from pre-operative values. Differences were considered statistically significant for p-values < 0.05 . The correlation coefficients between subjective and objective measures were computed using Pearson's correlation coefficient.

RESULTS

Airspace cross-sectional areas were computed perpendicular to flow streamlines and plotted as a function of distance from nostrils in 15 NAO patients pre- and post-surgery. The results for two patients are illustrated in Figure 3. Patient A underwent septoplasty alone, which increased the $mCSA$ area in the left cavity, while decreasing the $mCSA$ in the right cavity (Figure 3 – Top row). A symmetrical distribution of left-to-right $mCSA$ was achieved post-surgery. Patient B underwent septoplasty combined with bilateral inferior turbinate reduction. An increase in the airspace cross-sectional area was observed in both nasal cavities (Figure 3 – Bottom row). These results illustrate how our computational streamline rhinometry method can be used to quantify anatomical changes after nasal surgery.

The smallest mCSA among the 10 streamlines increased from a pre-surgery average of $(0.28 \pm 0.18) \text{ cm}^2$ to a post-surgery average of $(0.43 \pm 0.12) \text{ cm}^2$ in the most obstructed cavity ($p = 0.0002$) (Figure 4). This increase in mCSA was accompanied by a reduction in nasal resistance from $(0.51 \pm 0.56) \text{ Pa.s/ml}$ pre-surgery to $(0.20 \pm 0.11) \text{ Pa.s/ml}$ post-surgery in the most obstructed side ($p = 0.021$). In the least obstructed cavity, neither the average mCSA ($0.67 \pm 0.21 \text{ cm}^2$ pre-surgery, $0.65 \pm 0.16 \text{ cm}^2$ post-surgery, $p = 0.74$) nor the average nasal resistance ($0.20 \pm 0.10 \text{ Pa.s/ml}$ pre-surgery, $0.16 \pm 0.09 \text{ Pa.s/ml}$ post-surgery, $p = 0.096$) were significantly affected by surgery (Figure 4).

The improvement in objective measures of nasal airflow was followed by an improvement in subjective scores of nasal patency. The NOSE score was reduced from 67 ± 19 pre-surgery to 23 ± 22 post-surgery, while the VAS score in the most obstructed side increased from 3 ± 2 pre-surgery to 7 ± 2 post-surgery. Subjective scores of nasal patency correlated with both mCSA and nasal resistance (Table 1). The highest correlation coefficient ($|r|=0.57$) was observed between mCSA and VAS in the most obstructed cavity.

Nasal resistance had an inverse relationship with mCSA (Figure 5A). Fitting the data with equation (5) provided $a = 0.101 \pm 0.008$ and $b = -0.82 \pm 0.08$ with a correlation coefficient of $|r| = 0.82$. Based on this fitting, the critical area beyond which constrictions elevate nasal resistance above the healthy range was predicted to be $A_{\text{crit}} = (R_{\text{crit}}/a)^{1/b} = 0.37 \text{ cm}^2$. Based on this critical area, the dataset was divided into two sub-samples and a higher correlation between R and mCSA was found for constricted nasal cavities ($|r|=0.92$) as compared to nonconstricted nasal cavities ($|r|=0.57$) (Figures 5B,5C). This confirmed the prediction that nasal resistance is more tightly coupled with the minimal cross-sectional area in severely constricted nasal cavities. Finally, fitting the data for severely constricted nasal cavities ($\text{mCSA} < 0.37 \text{ cm}^2$) with the orifice flow equation (equation (4)), an excellent fit was obtained ($|r| = 0.99$) and the discharge coefficient of the human nasal cavity was estimated to be $C_d = 0.49 \pm 0.02$ (Figure 5D).

DISCUSSION

The apparent lack of correlation between nasal resistance and the airspace minimal cross-sectional area is a long-standing problem in the field of rhinology. Many studies have investigated the correlation between nasal resistance measured via rhinomanometry and the airspace mCSA obtained with acoustic rhinometry (Table 2). The majority of these in vivo studies found a moderate correlation ($|r| = 0.4$ to 0.6), but some studies found no correlation at all (Table 2). This manuscript provides a theoretical framework to understand these puzzling results.

The Bernoulli Obstruction Theory predicts that nasal resistance is inversely proportional to the airspace minimal cross-sectional area, $R \propto (\text{mCSA})^{-1}$, but this tight coupling is only predicted to occur in severely constricted nasal cavities ($\text{mCSA} < A_{\text{crit}}$). In constricted nasal cavities, the constriction accounts for the majority of the transnasal pressure drop (Figure 6). Therefore, small changes in the minimum cross-sectional area will substantially affect nasal resistance, and a strong correlation is observed between R and mCSA (Figure 5B). In contrast, in noses with less severe constrictions, a more uniform distribution of resistance is

observed along the nasal cavity (Figure 6). Consequently, the dimensions of other regions of the nasal cavity have a significant contribution to nasal resistance, and a weaker correlation between R and $mCSA$ is observed (Figure 5C).

Our analysis predicts that airway constrictions, in an otherwise normal nasal cavity, must have $mCSA$ smaller than 0.37 cm^2 in order to dominate nasal resistance to the extent that there is a tight coupling between R and $mCSA$. Given that healthy individuals rarely have $mCSA < 0.37 \text{ cm}^2$ (Table 3), a strong correlation between R and $mCSA$ is not expected in healthy subjects. Even NAO patients often have $mCSA$ larger than 0.37 cm^2 (Table 3). This suggests that the correlation between R and $mCSA$ reported in previous in vivo studies was weakened by (1) not differentiating between constricted and non-constricted nasal cavities, (2) the assumption of a linear relationship between R and $mCSA$ in the majority of previous studies (see Supplementary Material), and possibly by (3) experimental error inherent to the rhinomanometry and acoustic rhinometry techniques (Carney et al., 2000; Clement and Gordts, 2005; Fisher et al., 1995; Tarhan et al., 2005).

The correlation between acoustic rhinometry measurements and subjective sensation of nasal airflow remains controversial (Andre et al., 2009). Nearly half of the publications in the field found no correlation between subjective scores of nasal patency and $mCSA$ (Table 4). We believe that the Bernoulli Obstruction Theory (Equation (4)) offers a biomechanical explanation for the weak correlation between subjective nasal patency and $mCSA$. Given that many subjects have $mCSA$ above the critical threshold $A_{crit} = 0.37 \text{ cm}^2$ (Table 3), we can conclude that in the majority of people nasal resistance cannot be accounted for by the area of a single narrow segment, but rather it reflects the summation of the contributions of all segments along the nasal airway. Hence, it is not surprising that $mCSA$ has a weak correlation with subjective perception of nasal airflow.

Some limitations of this work must be noted. First, the cohort studied was relatively small. This was partly due to the labor-intensive nature of investigating 10 streamlines per cavity and manually segmenting cross-sections with two disconnected regions, as described in the Supplementary Material. Importantly, the low variability of $mCSA$ values computed along different streamlines will allow future studies to select a single streamline representative of the airflow patterns, and thus the investigation of larger cohorts. Second, our cohort included mostly Caucasian patients, which is representative of the patient population in our clinical practice. Future analyses should include more ethnically diverse groups. Third, we focused on the relationship between nasal resistance and $mCSA$ only. Future studies should investigate the relationship between nasal resistance and the entire profile of nasal cross-sectional areas. Finally, our computational methods did not account for tissue compliance. While the assumption of rigid walls is a good approximation for the majority of patients, it does not hold for patients with nasal valve collapse.

In summary, we conclude that the relationship between nasal resistance and airspace minimal cross-sectional area can be described by the Bernoulli Obstruction Theory, which predicts

$$R = \frac{1}{C_d} \left(\frac{\rho \Delta p}{2} \right)^{\frac{1}{2}} \frac{1}{mCSA}$$

where the discharge coefficient of the nasal cavity is estimated to be $C_d = 0.49 \pm 0.02$. The theory predicts that a strong coupling between R and $mCSA$ is observed in severely constricted nasal cavities ($mCSA < A_{crit}$) when the constriction dominates the contributions to nasal resistance. Given that the majority of subjects have $mCSA$ above the threshold $A_{crit} = 0.37 \text{ cm}^2$, these airway constrictions are not predicted to be the exclusive cause of a pathologic increase in nasal resistance. Therefore, it is not surprising that $mCSA$ has a weak correlation with subjective nasal patency. Future studies should test these predictions in larger and more ethnically diverse cohorts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

The concept of computational streamline rhinometry. (LEFT) Flow streamlines were calculated using computational fluid dynamics. (RIGHT) Cross-sectional areas, calculated perpendicular to flow streamlines in the anterior nose and perpendicular to the nasal floor in the posterior nose, were plotted as a function of the distance from nostrils. The distance was normalized by the streamline length (i.e., Distance = 0 corresponds to nostril; Distance = 1 corresponds to choana). The shape of seven cross-sections and their locations in the area-distance curve are illustrated.

Figure 2.

Nasal cross-sectional areas were averaged among ten streamlines. (LEFT) Three-dimensional model of the nasal cavity displaying the 10 streamlines used to compute cross-sectional areas in the pre-surgery right nasal cavity of one NAO patient. (RIGHT) Cross-sectional area vs. distance from the nostril along each of the ten streamlines (black lines) and the average area-distance curve among all streamlines (red line).

Figure 3.

Pre-surgery vs. post-surgery nasal cross-sectional areas in two NAO patients. (TOP PANELS) Patient A underwent septoplasty alone, which increased the minimal cross-sectional area (mCSA) in the left cavity and decreased mCSA in the right cavity. A symmetrical distribution of left-to-right mCSA was achieved post-surgery. (BOTTOM PANELS) Patient B underwent septoplasty combined with bilateral inferior turbinate reduction. An increase in the airspace cross-sectional area was observed in both nasal cavities.

Figure 4.

Average minimal cross-sectional area and nasal resistance in a cohort of 15 NAO patients pre-surgery and post-surgery. The unilateral nasal cavities were assigned as most obstructed or least obstructed based on the pre-operative VAS scores. Asterisk (*) denotes statistical significance at level $p < 0.05$; N.S. = non-significant.

Figure 5.

(A) Unilateral nasal resistance vs. minimal cross-sectional area in the entire cohort ($n = 60$ nasal cavities corresponding to 15 NAO patients pre- and post-surgery). A power law curve fit provided a correlation of $|r| = 0.816$. (B) and (C) The correlation between R and $mCSA$ was stronger in nasal cavities with $mCSA < 0.37 \text{ cm}^2$ ($|r| = 0.921$) than in nasal cavities with $mCSA > 0.37 \text{ cm}^2$ ($|r| = 0.572$). (D) Fitting the CFD-derived nasal resistance with the orifice flow equation yielded a discharge coefficient $C_d = 0.49 \pm 0.02$.

Figure 6.

Illustration of how severe airway constrictions contribute disproportionately to nasal resistance. (A) Lateral view of a nasal cavity model showing uniformly spaced coronal planes (D = distance from nostrils divided by the length of septum). (B) Pressure drop in each of the eleven segments defined in panel (A). In the left cavity, most of the pressure drop occurs in the nasal vestibule (nostril to $D=0$) due to a severe constriction located in that segment ($mCSA = 0.12 \text{ cm}^2$). In the right cavity, the nasal vestibule was wider ($mCSA = 0.66 \text{ cm}^2$), thus the 19 Pa pressure drop was distributed more evenly throughout the nasal cavity.

Table 1

Pearson correlation between subjective and objective measures of nasal patency. All results were statistically significant ($p < 0.05$).

	NOSE score	VAS score
Minimal cross-sectional area	−0.46	0.57
Nasal resistance	0.38	−0.44

Abbreviations: NOSE = Nasal Obstruction Symptom Evaluation; VAS = Visual Analog Scale. Except for the NOSE score, which is a bilateral measure, all other variables are unilateral values in the pre-operatively most obstructed nasal cavity.

Table 2

Summary of research papers that investigated the correlation between nasal resistance measured with rhinomanometry and the airspace minimal cross-sectional area obtained with acoustic rhinometry.

REFERENCE	SAMPLE SIZE	NASAL CAVITY	CORRELATION COEFFICIENT	
Healthy Subjects				
(Kesavanathan et al., 1996) ^a	N = 32	Unilateral	ETS non-sensitive:	r = 0.52
	N = 26		ETS sensitive:	r = 0.49
	N = 16	Bilateral	ETS non-sensitive:	r = 0.04
	N = 13		ETS sensitive:	r = 0.18
(Numminen et al., 2002)	N = 249	Unilateral	N.S.	
(Wandalsen et al., 2012)	N = 20	Unilateral	Baseline:	r = 0.44
			Induced obstruction:	r = 0.61
			Decongestant:	r = 0.43
(Zhao et al., 2014)	N = 22	Unilateral	N.S.	
NAO Patients				
(Roithmann et al., 1994) ^b	N = 142	Unilateral	Pre-decongestion:	r = 0.95
			Post-decongestion:	r = 0.97
(Scadding et al., 1994)	N = 24	Unilateral	r = 0.6	
(Tai et al., 1998)	N = 39	Unilateral	r = 0.43	
	N = 78	Bilateral	r = 0.58	
(Passali et al., 2000)	N = 60	Unilateral	N.S.	
(Naito et al., 2001)	N = 50	Unilateral	N.S.	
(Masdeu et al., 2011)	N =14	Unilateral	Sitting:	r = 0.27
			Supine:	r = 0.52
(Wandalsen et al., 2012)	N = 20	Unilateral	Baseline:	r = 0.32
			Induced obstruction:	r = 0.54
			Decongestant:	r = 0.49
General Population				
(Yepes-Nunez et al., 2013)	N = 184	Unilateral	r = 0.496	

^aEnvironmental tobacco smoke (ETS) non-sensitive: subjects reported no history of rhinitis on exposure to ETS; ETS sensitive: subjects reported a history of ETS-induced rhinitis

^bEquation used for correlation: $mCSA = a e^{-b R}$

Abbreviation: N.S. = Non-significant

Table 3

Minimal cross-sectional area (mCSA) in healthy subjects and nasal airway obstruction (NAO) patients reported in the acoustic rhinometry literature. All values refer to unilateral measurements without decongestion.

COHORT	mCSA (cm ²)	SAMPLE SIZE	REFERENCE
Healthy subjects			
Control group	0.72 ± 0.02	N = 11	(Hilberg et al., 1990)
Caucasians	0.73 ± 0.2	N = 134	Lenders and Pirsig, 1990)
Danish	0.73 ± 0.02	N = 82	(Grymer et al., 1991)
Oriental	0.62 ± 0.19	N = 20	(Morgan et al., 1995)
Caucasian	0.71 ± 0.15	N = 20	
Negro	0.88 ± 0.22	N = 20	
Indians	0.70 ± 0.16	N = 20	(Gurr et al., 1996)
Anglo-Saxons	0.71 ± 0.15	N = 20	
Asian	0.53 ± 0.10	N = 24	(Corey et al., 1998)
Black	0.67 ± 0.10	N = 22	
White	0.52 ± 0.12	N = 53	
Chinese	0.75 ± 0.03	N = 37	(Huang et al., 2001)
Indians	0.75 ± 0.03	N = 34	
Malays	0.72 ± 0.04	N = 18	
Overall	0.74 ± 0.02	N = 89	
Both sides	0.58 ± 0.18	N = 102	(Larsson et al., 2001)
Wider side	0.67 ± 0.23		
Narrower side	0.49 ± 0.17		
White	0.68	N = 249	(Numminen et al., 2002)
NAO patients			
Pre-operative	0.62 ± 0.06	N = 17	(Hilberg et al., 1990)
Group A		N = 37	(Grymer et al., 1993) ^a
Pre-operative, OS	0.24 ± 0.01 *		
Post-operative, OS	0.50 ± 0.02 *		
Group B		N = 37	
Pre-operative, OS	0.46 ± 0.02 *		
Post-operative, OS	0.66 ± 0.03 *		
NAO patients	0.51 ± 0.02	N = 78	(Roithmann et al., 1994)

COHORT	mCSA (cm ²)	SAMPLE SIZE	REFERENCE
Pre-operative	0.55 ± 0.03 [*]	N = 24	(Shemen and Hamburg, 1997)
Post-operative	0.63 ± 0.02 [*]		
Pre-operative, OS	0.38 ± 0.18 [*]	N = 50	(Illum, 1997)
Post-operative, OS	0.49 ± 0.17 [*]		
Pre-operative, OS	0.47 [*]	N = 27	(Reber et al., 1998)
Post-operative, OS	0.58 [*]		
Other groups			
Cosmetic rhinoplasty		N = 37	(Grymer, 1995)
Pre-surgery, NS	0.58 ± 0.02 [*]		
Post-surgery, NS	0.44 ± 0.02 [*]		
Sleep disordered breathing	0.58 ± 0.13	N = 44	(Morris et al., 2005)

^a Group A = pronounced septal deviation. Group B = less important septal deviation.

* Statistically significant difference between post-operative and pre-operative values.

Abbreviations: OS = obstructed side. NS = narrow side.

Table 4

Correlation between minimal cross-sectional area measured by acoustic rhinometry and subjective scores of nasal patency in non-decongested noses as reported in the literature.

COHORT	CORRELATION COEFFICIENT	SUBJECTIVE SCALE	SAMPLE SIZE	REFERENCE
Healthy subjects				
Healthy adults, group 1	$ r = 0.51$	Unilateral SSS	N = 16	(Kesavanathan et al., 1996) ^a
Healthy adults, group 2	$ r = 0.20$	Unilateral SSS	N = 13	
Healthy adults, group 1	$ r = 0.32$	Bilateral SSS	N = 16	
Healthy adults, group 2	N.S.	Bilateral SSS	N = 13	
Healthy adults	N.S.	Unilateral VAS	N = 10	(Gungor et al., 1999)
Healthy adults	N.S.	Unilateral SSS	N = 102	(Larsson et al., 2001)
Healthy adults	N.S. N.S.	Unilateral VAS Bilateral VAS	N = 44	(Zhao et al., 2011)
NAO patients				
NAO patients	$ r = 0.86$	Bilateral VAS	N = 16	(Marais et al., 1994) ^b
NAO patients	$ r = 0.53$	Unilateral VAS	N = 78	(Roithmann et al., 1994)
NAO patients	N.S.	Bilateral VAS	N = 27	(Reber et al., 1998)
NAO patients	N.S.	Unilateral VAS	N = 50	(Szucs and Clement, 1998)
NAO patients	N.S. N.S.	Unilateral VAS Bilateral VAS	N = 39	(Tai et al., 1998)
NAO patients	$ r = 0.23$	Bilateral SSS	N = 113	(Pirila and Tikanto, 2001)
Patients undergoing nasal or sinus surgery	N.S.	Bilateral SSS	N = 50	(Naito et al., 2001)
Other groups				
Allergic rhinitis patients	$ r = 0.75$	Bilateral SSS	N = 15	(Wang et al., 2004) ^c
Sleep disordered breathing patients	$ r = 0.45$	Bilateral SSS	N = 44	(Morris et al., 2005)
Patients evaluated for obstructive sleep apnea	N.S. $ r = 0.10$	NOSE Bilateral VAS	N = 237 N = 253	(Lam et al., 2006)
Clinicians attending an educational course	$ r = 0.27$ N.S.	Bilateral SSS Bilateral VAS	N = 184	(Yepes-Nunez et al., 2013)

^aGroup 1: environmental tobacco smoke (ETS) non-sensitive; group 2: ETS sensitive.

^bThe surgical change in mCSA (rather than mCSA alone) was used as the independent variable.

^cMeasurements after nasal allergen challenge.

Abbreviations: N.S. = non-significant; VAS = visual analog scale; SSS = symptom severity score; NOSE = Nasal obstruction symptom evaluation.