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How Nasal Cavity Structure Influences Empty Nose Syndrome Severity: A CFD-Based Analysis

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ABSTRACT

Empty nose syndrome (ENS) is an iatrogenic condition that can occur after partial, total turbinectomy, or cauterization of the turbinates. It leads to an altered sensation of nasal airflow, breathing difficulties, sleep disturbances, and other symptoms, such as nasal dryness. Although ENS is often diagnosed using questionnaires such as the ENS6Q, SNOT-20, SNOT-25 or cotton test, its precise causes are not yet well understood. Some patients with significant loss of nasal turbinates develop minor symptoms of ENS, while others present strong symptoms after cauterization of the mucosa. It is essential to understand the structural and aerodynamic factors contributing to ENS in order to improve diagnosis, prevention, and treatment. This study aims to identify correlations between ENS6Q score and anatomical and aerodynamic parameters obtained from computational fluid dynamics (CFD) simulations in ENS patients. We constructed 3D models of each patient's nasal cavity from their computed tomography (CT) scans and performed CFD simulations. Analysis focused on five parameters: remaining turbinate volume, total mucosal surface area, nasal resistance, mean cross-sectional area, and airflow imbalance between the two nasal cavities. These parameters were then compared with ENS6Q scores. The results suggest that lower residual nasal turbinate volume and reduced mucosal surface are associated with higher ENS6Q scores. In addition, significant asymmetry of airflow between the two nasal cavities seems to be correlated with more severe symptoms as well. Finally, our data indicates that people with larger nasal cavities and, therefore, a larger preoperative mucosal surface tend to be more resilient to turbinectomy. For equivalent turbinate resection, patients with initially smaller nasal cavities and therefore less mucosal surface area have more severe ENS symptoms. By quantifying the anatomical and aerodynamic characteristics of patients with ENS, this study provides new insights into the structural factors contributing to the severity of ENS. These results could help refine diagnostic criteria and guide surgical techniques to minimize the risk of ENS. In addition, a better understanding of ENS could help to develop new treatments, both surgical and non-surgical.

Keywords: Empty Nose Syndrome (ENS), Computational Fluid Dynamics (CFD), Nasal Turbinates, Mucosal Surface Area

Key Messages:

- Reduced mucosal surface area and turbinate volume are strongly correlated with greater Empty Nose Syndrome (ENS) severity.

- Airflow asymmetry between nasal cavities contributes to increased ENS symptoms.

INTRODUCTION

Empty Nose Syndrome (ENS) was first described by Kern and Stenkvist[1] and popularized by Dr. Steven Houser. It refers to a set of symptoms that may occur after partial or total turbinectomy or simple laser cauterization. The turbinates are made up of bony plates surrounded by erectile tissue covered with a mucous membrane. Their purpose is to humidify, filter, and warm the air before it reaches the lungs. They also inform the brain of the passage of airflow via, among other things, TRPM8 receptors[2]. These are thermoreceptors that sense cold in two ways. The air entering the nasal cavity is generally colder than the mucous membrane, which is maintained at around 37°C. Some of the mucus on the surface of the mucous membrane evaporates on contact with the air flow, causing the water it contains to change from a liquid to a gas. This change of state consumes energy and therefore cools the mucous membrane. TRPM8 receptors are also sensitive to menthol, which also causes a sensation of cold.

Partial or total removal of the turbinates can cause empty nose syndrome, and simple cauterization of the mucosa without volume reduction can also cause it due to the alteration of the health of the mucosa. There are three types of turbinates in the nasal cavity: inferior, middle, and superior. The most common surgery is inferior turbinectomy, but middle turbinectomy also exists and can cause symptoms of empty nose syndrome. People suffering from Empty Nose Syndrome have difficulty feeling the passage of air, which causes a feeling of suffocation and disrupts breathing and sleep. Nasal dryness, a feeling of cold air, and infections are also common symptoms.

Current treatments available fall into two categories: invasive and non-invasive. Saline sprays or nasal creams are used to reduce nasal dryness. Alternatively, living in a humid climate or humidifying living spaces can also help. There are also more invasive treatments, such as injections of hyaluronic acid or autologous fat fillers, which aim to reduce the cross-sectional area. There are also autologous or exogenous rib or ear cartilage implants, which have the same purpose as fillers but are generally more permanent. ADSCs (Adipose-derived stem cells) or MSCs (Mesenchymal stem cells) stem cell injections are also beginning to be used to reduce scar tissue and improve overall mucosal health[3].

Computational fluid dynamics (CFD) simulation allows the study of airflow. CFD simulations can quantify critical parameters such as nasal resistance, airflow velocity, and wall shear stress (WSS). The latter is an indicator of mucosal stimulation caused by airflow. Several previous studies have used CFD to demonstrate that patients with ENS have lower nasal resistance and altered airflow distribution, as well as reduced stimulation throughout the lower meatus[4]. In this study, we perform CFD simulations on nasal cavity models based on computed tomography (CT) scans of patients with ENS in order to characterize their airflow patterns and compare these results with the severity of symptoms quantified using the ENS6Q questionnaire. Our goal is to better understand the mechanisms that cause ENS, with the aim of finding better treatments and reducing the risks associated with nasal cavity surgery.

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METHODS

Problem Statement

To diagnose empty nose syndrome, two questionnaires are often used: ENS6Q (Empty Nose Syndrome 6-item Questionnaire) and SNOT 20 or SNOT 25 (Sino-Nasal Outcome Test). Above a certain score, the person is considered to be suffering from ENS. Other diagnostic tools can also be used, such as the cotton test, which simulates the placement of an implant, or the injection of a filler such as hyaluronic acid into the remaining turbinates or other areas of the nasal cavity to simulate an implant.

Some people with reduced turbinate volume do not necessarily suffer from empty nose syndrome, although they often still experience certain symptoms such as nasal dryness. Conversely, other people who have undergone cauterization do suffer from it. It is therefore not yet clear exactly what causes empty nose syndrome. However, we already have a general understanding of what causes ENS. There are two main points. (1) The amount of turbinate tissue removed: the more tissue removed, the higher the risk of ENS. (2) The health of the nasal mucosa: the more non-functional tissue remains, the higher the risk.

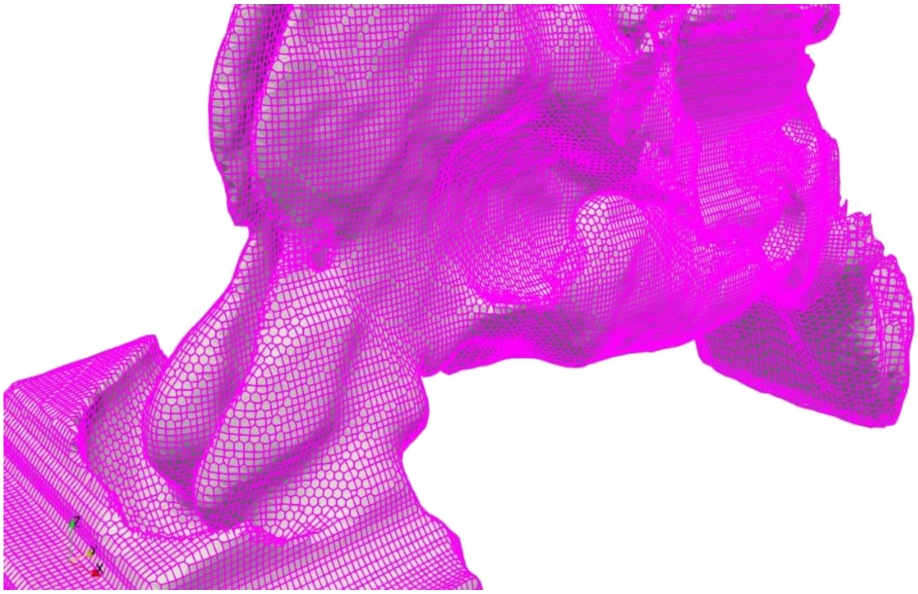
The aim of this study is to shed light on the specific causes of ENS by identifying correlations between the ENS6Q score and various data obtained from fluid simulations of a cohort of patients whose turbinates have been partially or completely removed.

Study Design and Patients

We simulated airflow in the nasal cavity of 19 people using a suite of open-source software. Each patient had to complete an ENS6Q questionnaire to assess their symptoms. The questionnaire consists of six questions that provide information on nasal dryness, sensation of airflow, suffocation, sensation of an empty nose, nasal crusting, and finally, a burning sensation. In this study, we recruited patients clinically diagnosed with ENS. The inclusion criteria were: 1/ a history of partial or total resection of the inferior or middle turbinates with persistent ENS symptoms for at least six months post-surgery; 2/ A good-quality CT-scan with slices spaced at a maximum of 1 mm 3/ The absence of other significant nasal pathology. The severity of ENS symptoms was quantified using the ENS6Q questionnaire. Formal ethical approval was not sought from an Institutional Review Board for this small-scale pilot project, as the study was conducted for internal purposes. All participants were fully informed of the study's purpose, participation was voluntary, and all data were collected and stored with strict confidentiality and anonymity. The study was conducted in accordance with the Declaration of Helsinki, and formal ethical approval will be sought for any future expansion of this research.

Nasal Airway Modeling

The patient CT-scans were converted to 3D in .STL format using the open-source software SLICER 5.2, with part of the air surrounding the nostrils and part of the pharynx retained.
The nasal cavity was meshed using OpenFoam software (version 1812). Depending on the case, it contains between 500,000 and 1 million cells, and an example of the mesh is shown in Figure 1. Beyond 1 million cells, we did not observe any significant differences in the simulation results.



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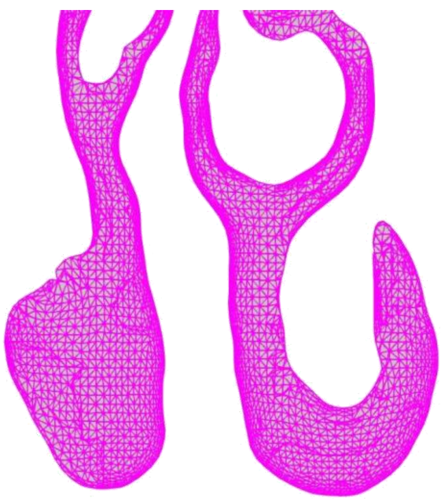

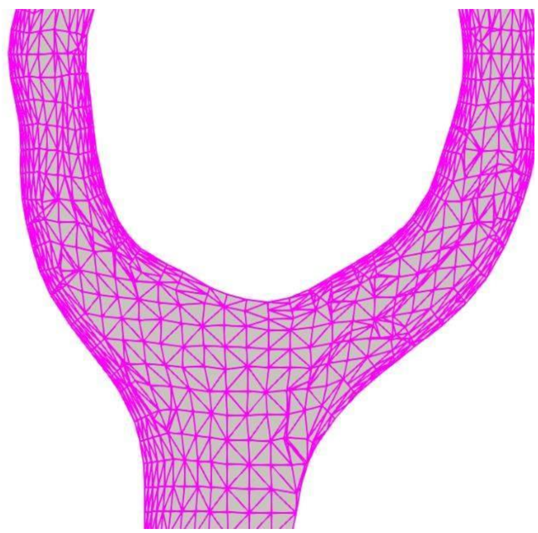

B **C**

Figure 1. 3D reconstruction of the nasal cavity generated from CT data. **A.** 3D meshing view **B & C**. Cross-section view in the coronal axis. There are around 700k cells in this model.

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CFD Simulation
The CFD simulations were performed using OpenFoam software (version 1812). We assumed steady-state incompressible air flow. We defined an inspiratory flow rate of 15 l/min. Air was considered a Newtonian fluid with the following characteristics: a density of 1.2 kg/m3 and a dynamic viscosity of $1{,}8\times10^{-5}$ Pa·s. We applied a flow rate boundary condition at the nostril inlet and a constant pressure of 0 Pa at the pharynx. Solver: SIMPLE. Turbulence model: RANS k epsilon. The temperature and humidity parameters of the walls were not taken into account.
We used the SIMPLE solver (Semi-Implicit Method for Pressure-Linked Equations) because the air is considered incompressible, given that the velocities do not exceed 5 m/s.
The RANS (Reynolds-Averaged Navier–Stokes) K epsilon turbulence model was used because it offers a good compromise between calculation time and physical realism of the air flow with light to moderate turbulence, as is the case in the study of the nasal cavity.

Finally, the simulation data was analyzed using the open-source software Paraview (version 13.0). We created graphs to visualize possible correlations between the ENS6Q score and each data point. We chose scatter plots with a regression line.

Each patient received a detailed simulation report, including:

- A 3D model of the airflow (Figure 2A).
- Airflow velocity distribution on cross-sections (Figure 2B & C).
- A 3D model of the Wall Shear Stress (Figure 3).
- A graph of the cross-sectional areas (Figure 7).
- A graph of the airflow imbalance between the two nasal cavities.

RESULTS

19 ENS patients (17 men, 2 women) were included. All patients had undergone partial or total resection of the inferior turbinates. The median ENS6Q score was 16 (range: 6–24), indicating moderate to severe symptoms. Fluid simulations and anatomical analysis allowed us to extract the data that we considered most relevant, namely, total nasal resistance, air flow imbalance between the left and right nasal cavities, average cross-sectional area, and average perimeter of the mucosa, which actually reflects the total mucosal surface area along the nasal cavity. We had to use the perimeter because the measurement was taken in sections. Finally, the percentage of remaining turbinates was quantified visually. We did not collect data on WSS because it was difficult to quantify. However, visualization of wall shear stress was useful in helping patients understand the cause of their loss of nasal sensation. Indeed, patients suffering from ENS have lower WSS values, especially in areas where volume has been removed.

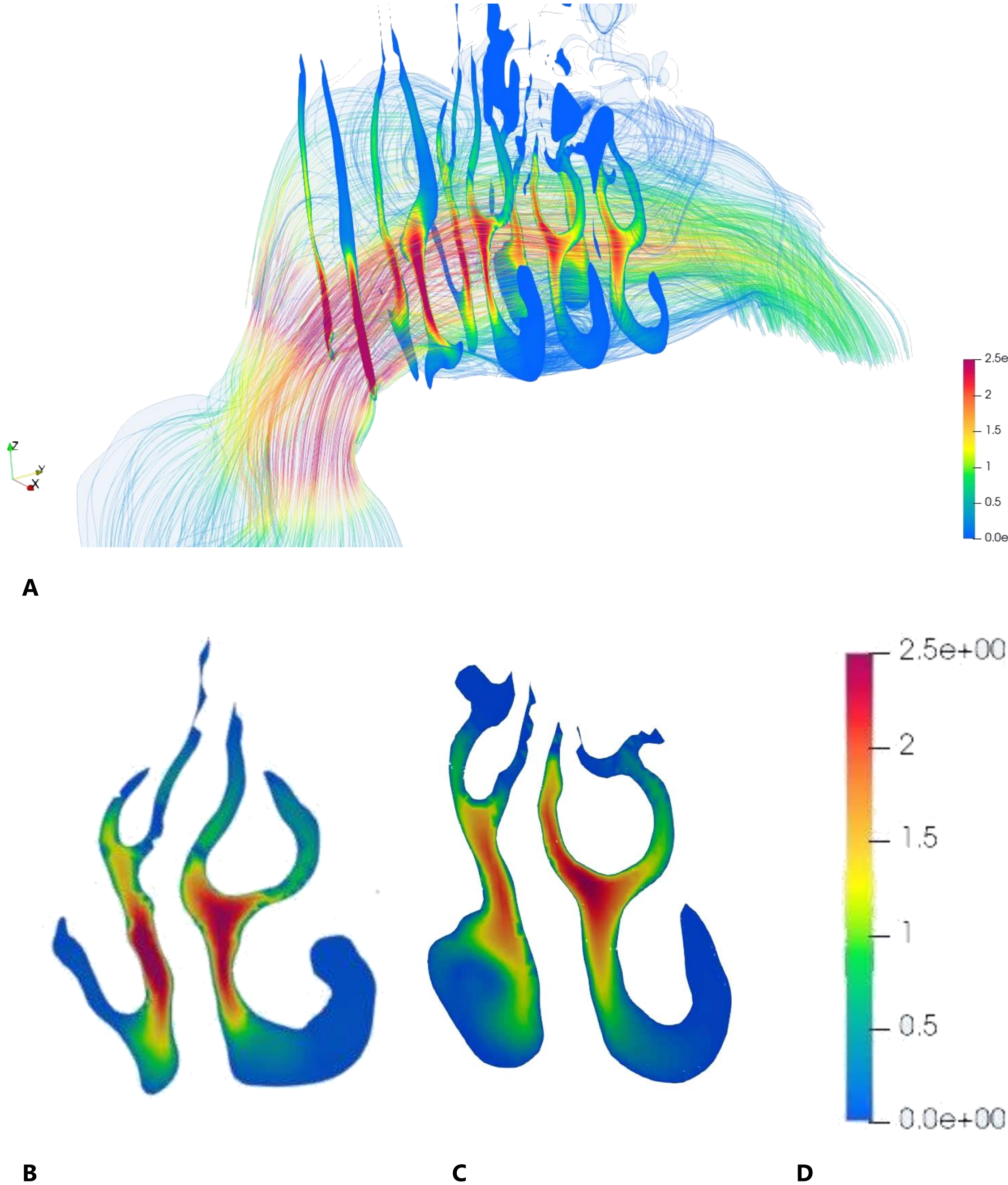

Figure 2. Airflow distribution in a representative ENS patient. **A.** 3D view of the airflow with sections. **B & C.** Views of the velocity distribution on coronal cross-sections located 20 mm and 30 mm from the nostrils **D.** Scale up to 2.5 m/s.

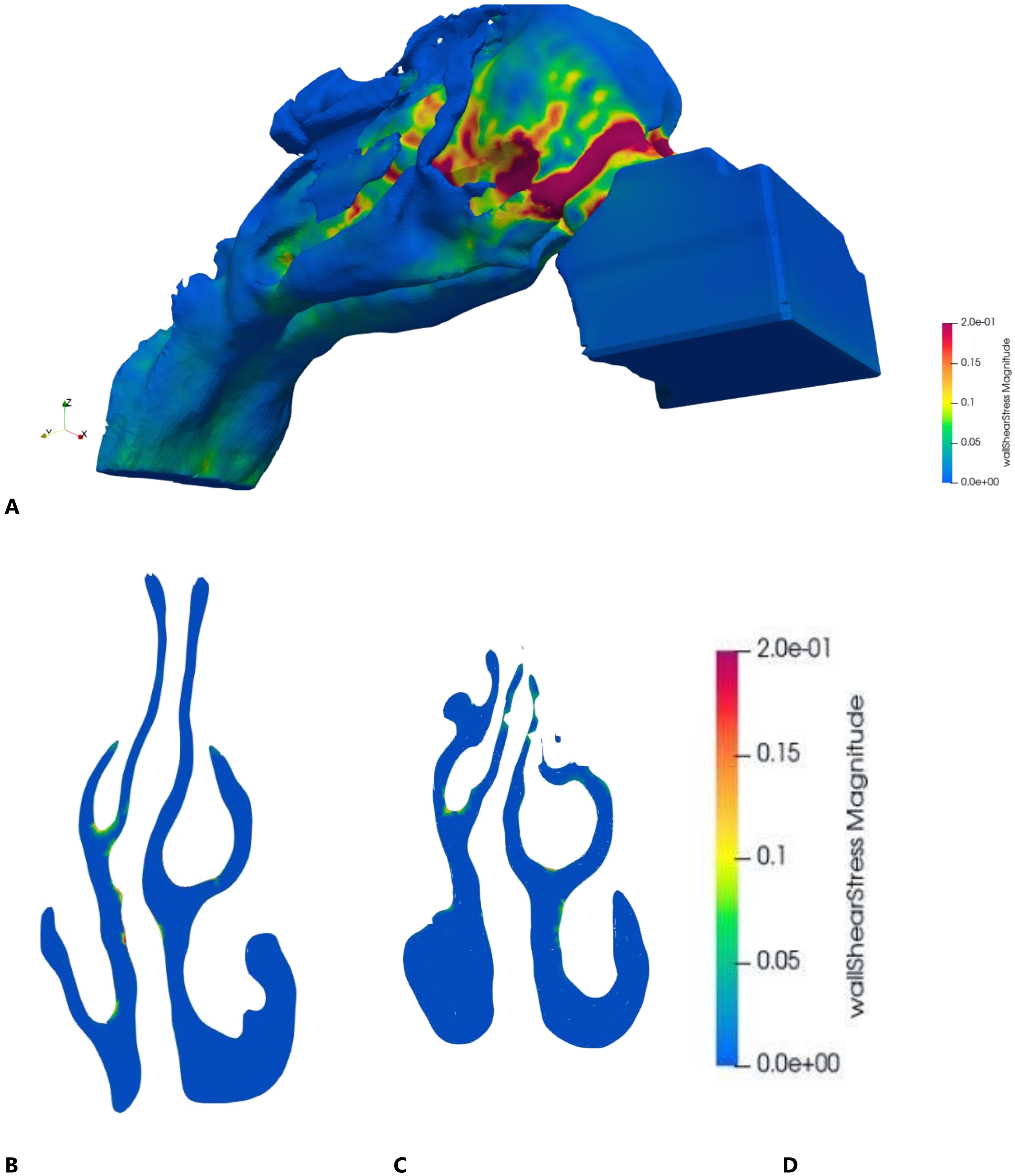

Figure 3. Wall shear stress distribution in a representative ENS patient. **A.** 3D view of Wall Shear Stress distribution **B. & C.** Wall Shear Stress distribution on coronal cross-sections located 20 mm and 30 mm from the nostrils **D.** Scale up to 0.2 Pa.

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In table 1, it should be noted that the cross-sectional and perimeter data for patient 9 are missing because he had very open sinuses. It was therefore impossible to measure his values accurately.

Table 1. Data extracted from anatomical analysis and fluid simulations.

Subjects	DeltaP (Pa)	Airflow imbalance (ratio)	Average cross sectional area (mm^2)	Percentage remaining turbinate (left)	Percentage remaining turbinates (right)	Average remaining turbinate (%)	Average perimeter (mm)	ENS6Q total
1	10.50	1.27	320	50	0	25	306	19
2	4.9	2.34	370	90	0	45	314	20
3	8	1.67	327	70	90	80	398	10
4	8.7	1.12	412	70	10	40	304	10
5	6.8	2.19	345	20	70	45	314	17
6	10.2	1.10	307	90	70	80	353	6
7	4.1	1.05	500	90	70	80	282	11
8	6.75	3.00	291	90	70	80	290	16
9	5	1.05	-	40	30	35	-	16
10	7.2	2.17	336	100	80	90	355	20
11	12.5	1.10	315	40	50	45	276	26
12	13.5	1.50	275	80	90	85	304	10
13	3.6	1.27	492	50	50	50	311	10
14	12.7	1.00	245	70	70	70	301	19
15	6	1.10	399	90	90	90	366	12
16	8.3	1.25	301	70	70	70	289	22
17	5	1.40	360	20	80	50	260	17
18	7.6	1.20	252	80	90	85	281	13
19	12.75	1.90	201	90	50	70	216	24

In table 2, among the parameters analyzed, the perimeter of the mucosa showed the strongest negative correlation ($r = -0.5$, p-value = 0.034). The more mucosa remains, the lower the ENS6Q score, suggesting that individuals with a larger initial mucosal surface area may be more resistant to the effects of turbinectomy and experience fewer symptoms for the same level of aggressiveness of the procedure. The average cross-sectional area also shows a moderate negative correlation ($r = -0.417$), with a value ($p = 0.0848$) that is close to being statistically significant. The other parameters with weaker correlations are not statistically significant. These results highlight the potential impact of nasal cavity structure on the severity of ENS-related symptoms.

Table 2. Correlation coefficient r and statistical significance level p-value of the 5 data points.

	r	p-value
DeltaP	0.268	0.267
Airflow imbalance	0.246	0.31
Average cross-sectional area	-0.417	0.0848
Remaining turbinates	-0.297	0.217
Mucosal perimeter	-0.5	0.034

Pressure Loss

In Figure 4, DeltaP represents the pressure or load loss caused by the nasal cavity and part of the pharynx during the inspiratory phase. The unit is in Pascals (Pa). It can be compared to nasal resistance. This graph shows a weak correlation between nasal resistance and the ENS6Q score (r = 0.268), which is not statistically significant (p-value = 0.267). It is interesting to note that higher resistance is associated with a higher symptom score, which may seem counterintuitive at first glance. One might expect opposite results, given that a reduction in volume leads to a decrease in nasal resistance. Several factors may explain this result. First, the simulation includes the pharynx, which alters the result. For example, a small pharynx increases total resistance. A more accurate assessment of nasal resistance could have been obtained by excluding the pharynx and limiting the analysis to the area from the nostrils to the choanae. Second, a larger nasal cavity is associated with more mucosa and offers less resistance to airflow. And as we saw earlier, the total surface area of the mucosa is strongly correlated with the symptom score.

Quantity of Turbinates Remaining

The number of remaining turbinates was quantified visually, as no software is currently available to measure this data. In Figure 5, we observe a weak negative correlation between the percentage of remaining turbinates and the ENS6Q score (r = −0.297, p-value = 0.217). Although this suggests that having more turbinates is associated with fewer symptoms, the correlation is weak and not statistically significant. These results are not surprising and reflect the fact that the aggressiveness of turbinectomy affects the severity of symptoms. Additional studies with larger samples may be needed to confirm this trend and thus achieve a p-value < 0.05.

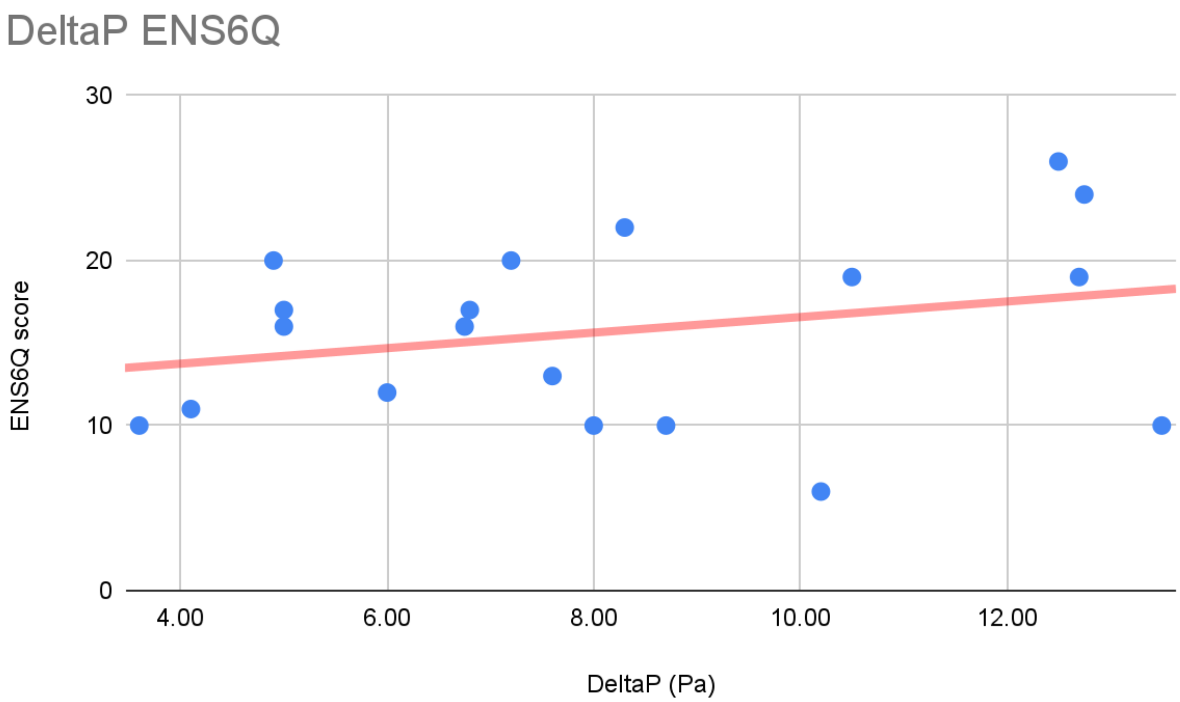

Figure 4. Correlation between nasal resistance (ΔP) and ENS6Q scores.

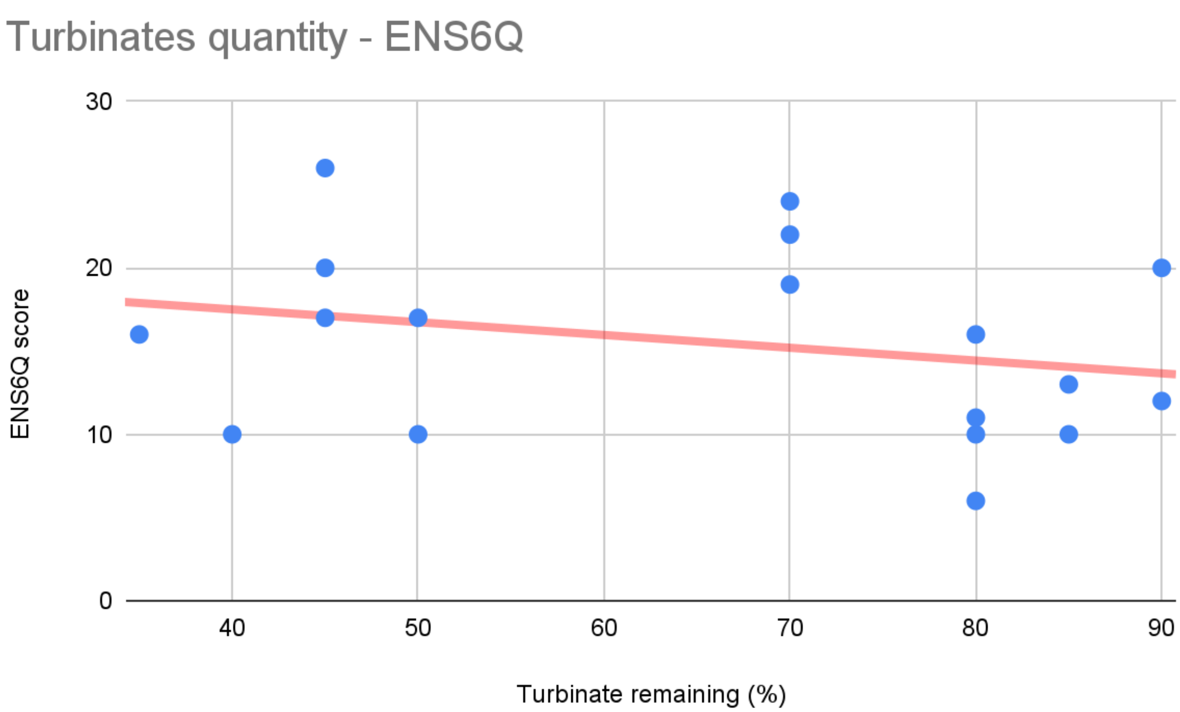

Figure 5. Percentage of remaining turbinate tissue compared with ENS6Q scores.

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Mucosal Surface

In Figure 6 the amount of mucosa was measured as follows: we made three cuts, starting 20 mm from the nostrils: one cut at 20 mm, one at 30 mm, and one at 40 mm. Then, we measured the perimeter and calculated the average. The result obtained is therefore an average perimeter in mm representing the surface area of the mucosa between 20 and 40 mm from the nostrils. We chose these sections because they represent the center of the nasal cavity, where the turbinates are generally cut the most during turbinectomies. Here, the correlation is even clearer, and we believe this is the most relevant result of the study. The mucosal perimeter data show the strongest negative correlation with the ENS6Q score ($r = -0.5$, p-value = 0.034), making this result statistically significant.

The more mucosa remains, the lower the ENS6Q score, regardless of all other results. In other words, a person who has undergone a more aggressive turbinectomy than another but who has a greater amount of remaining mucosa will still have fewer symptoms. The variation in the amount of mucosa in a nasal cavity is explained not only by the amount of the remaining turbinates but also by the size of the nasal cavity, which is largely correlated with the width of the dental arch and therefore the palate. This could explain, among other things, why some people experience fewer symptoms than others with the same amount of turbinate tissue removed. It is, of course, one of the parameters that can explain this phenomenon, but it is not the only one.

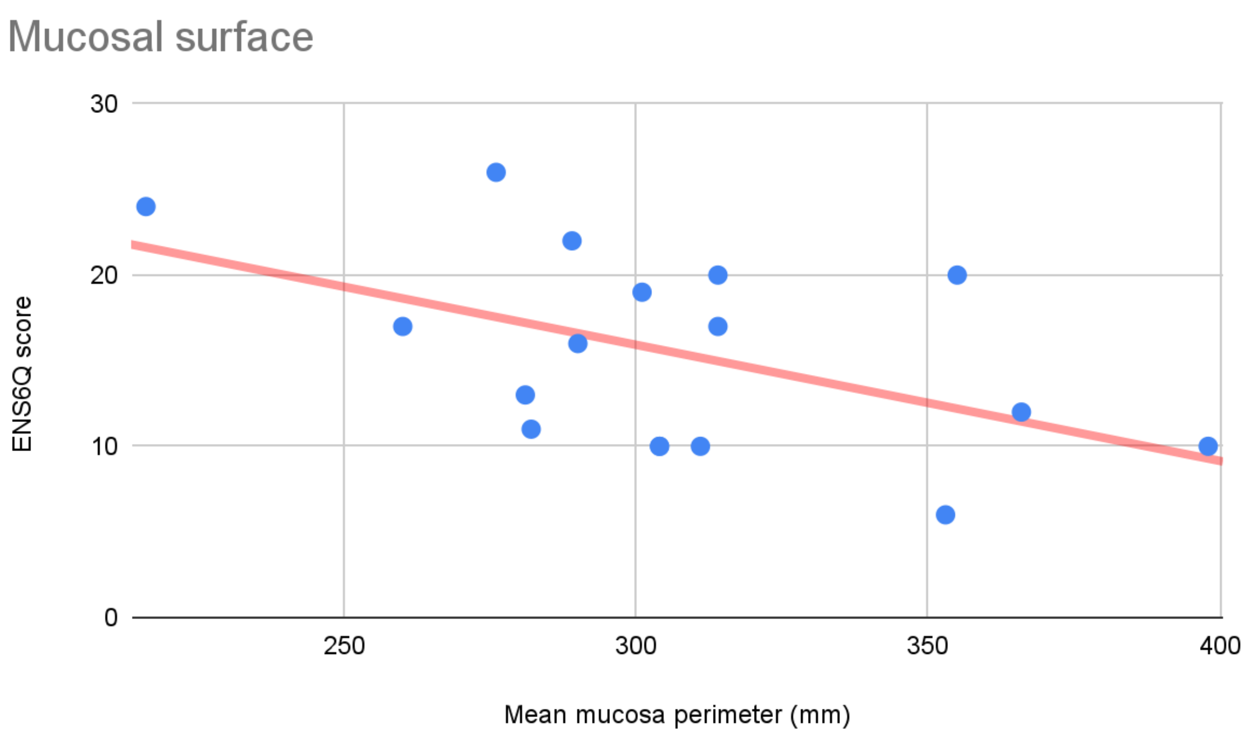

Figure 6. Correlation between mucosal perimeter and ENS6Q scores.

Average Cross-sectional Area

The average for the section was calculated as follows: we measured the cross-sectional area at 10 mm intervals, from the nostrils to a depth of 40 mm. The average of these measurements was then calculated, and the result is therefore expressed in mm^2.

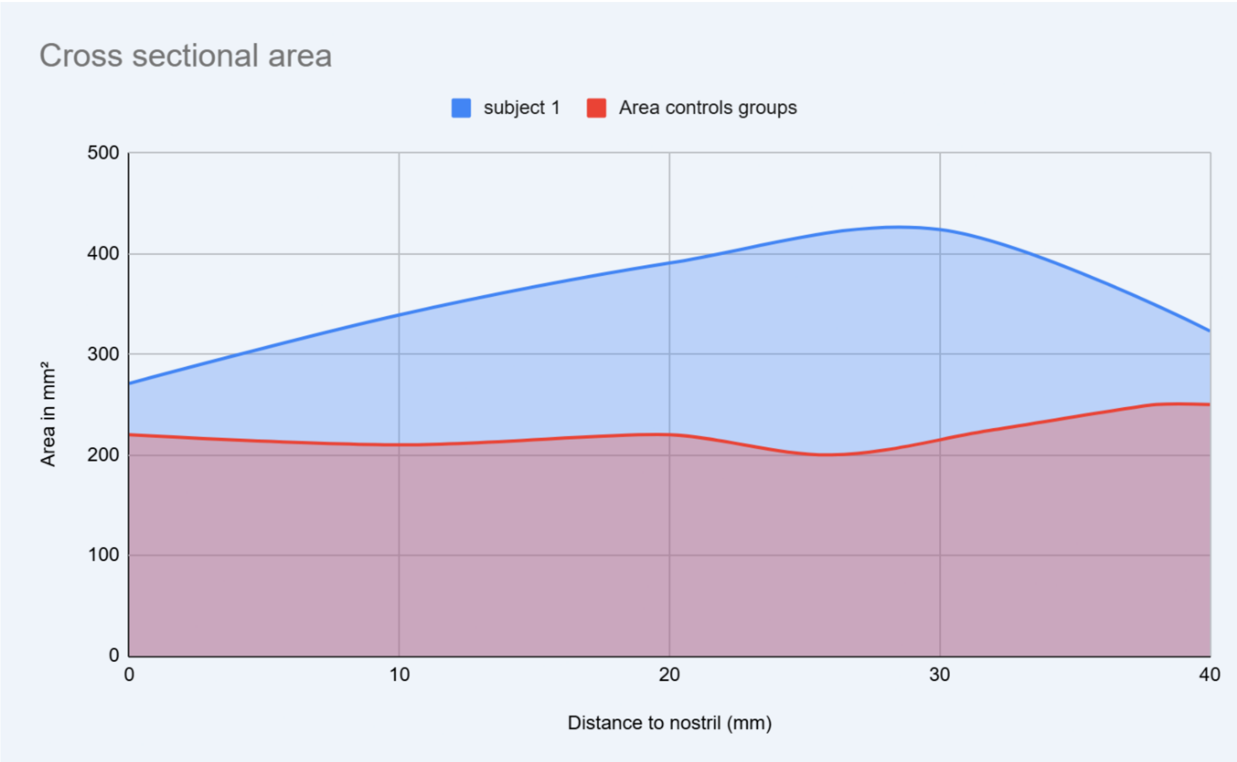

Figure 7. Example of cross-sectional measurement compared to a control group from a study[4].

In Figure 8, surprisingly, we observe a negative correlation between the transverse mean and the ENS6Q score ($r = -0.417$, p-value = 0.0848), which is relatively strong and close to the threshold of statistical significance. This seems counterintuitive, given that turbinectomy increases the transverse surface area and reduces nasal resistance. However, this can be explained. Subjects with a larger/more developed nasal cavity also have a higher cross-sectional area and, consequently, a larger mucosal surface area. As we saw earlier, the amount of mucosa is correlated with symptom reduction.

Airflow Imbalance

We measured the airflow on each side of the nasal cavity and then calculated a ratio to assess the severity of the imbalance between the two sides. In Figure 9, logically, the greater the imbalance, the higher the symptom score, as shown by the weak positive correlation ($r = 0.246$, p-value = 0.31). A recent CFD study uses this data, among other things, for the diagnosis of ENS[5]. A high imbalance represents an obstruction on one side and/or a side that is very open due to aggressive turbinectomy. This ultimately creates significant respiratory discomfort.

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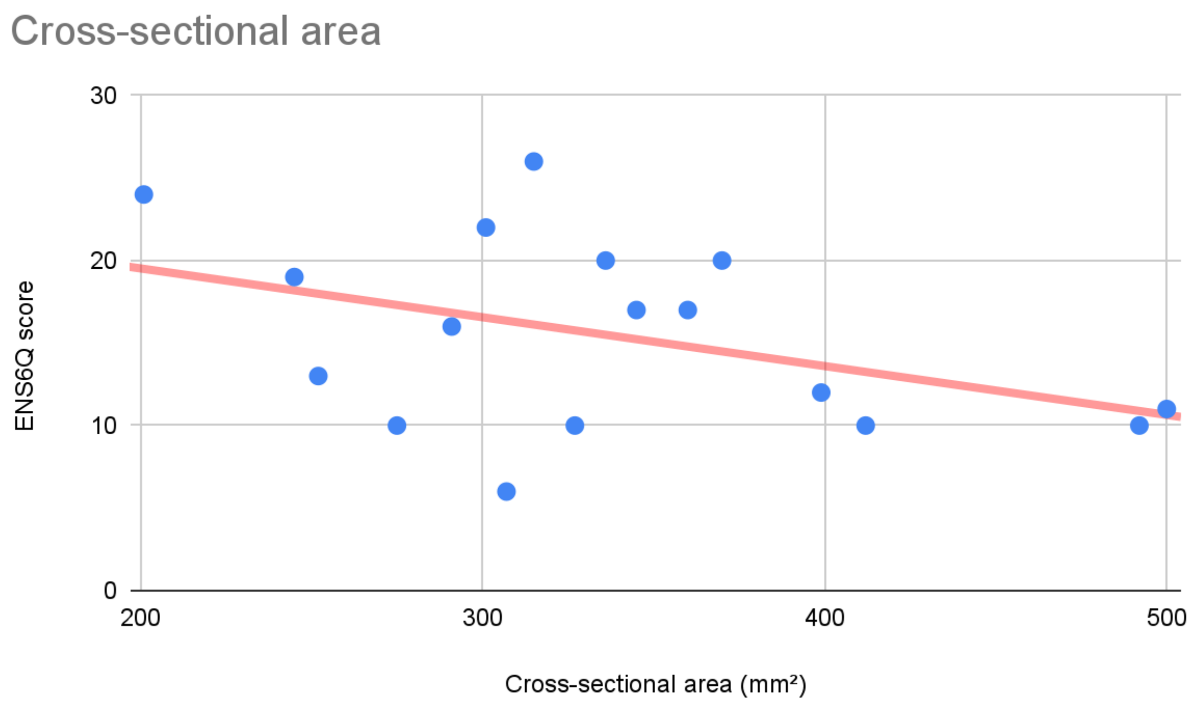

Figure 8. Correlation between average cross-sectional area and ENS6Q scores.

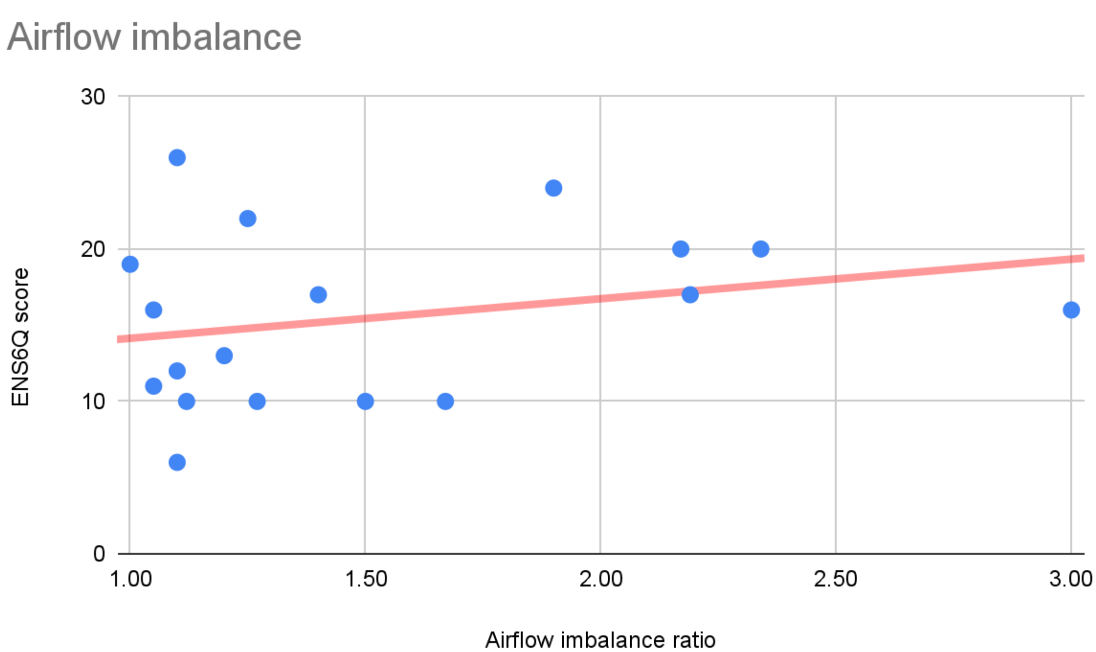

Figure 9. Correlation between airflow imbalance ratio and ENS6Q scores.

DISCUSSION

Firstly, the amount of the remaining turbinates and the total amount of mucosa are strongly correlated with the symptom score. In our opinion, this is an important point highlighted by this study. It should be noted that only the results for the total amount of mucosa are statistically significant. Theoretically, therefore, a person with a larger mucosal surface area due to a more developed nasal cavity will be more resilient to partial turbinectomy. This could partly explain why, with the same amount of turbinate removed, some people experience fewer symptoms than others. Of course, other factors come into play, such as the health of the mucosa. Secondly, the imbalance in airflow between the two sides of the nasal cavity creates significant discomfort, which influences the severity of symptoms.

LIMITATIONS

Our study is limited by its small sample size, which means that most of the results are not statistically significant. The gender imbalance could create a sampling bias, as it appears that nasal anatomy differs slightly between the sexes, which affects nasal resistance and other parameters[6]. Moreover, measuring the amount of the remaining turbinates is visual and not standardized, so it can be prone to errors. Also, our fluid study doesn't take into account temperature and humidity, which would have been interesting data. Furthermore, although we established strong correlations between anatomical measurements, CFD, and symptom severity, no direct measurements of nasal mucosal health were performed. Future studies incorporating airflow simulations, biological assessments of mucosal health, and, most importantly, a larger patient cohort would therefore be useful.

CONCLUSION

In summary, our anatomical analysis and CFD results from patients with ENS demonstrate that the aggressiveness of turbinectomies and airflow asymmetry are proportional to the ENS6Q symptom score. Our results suggest that preserving the mucosal surface, turbinate volume, and maintaining symmetrical airflow during nasal surgery are crucial strategies for minimizing the risk of ENS. Preserving mucosal health also plays an obvious role. Indeed, burns to the mucosa caused by the use of lasers are sufficient to create ENS symptoms[7]. Furthermore, individuals with a larger preoperative mucosal surface area may be more resistant to turbinectomy and experience fewer ENS symptoms.

Future studies involving a larger number of people would be necessary to achieve statistical significance across all results. Taking humidity and temperature data into account could also add interesting information. Finally, measuring and comparing the average WSS values of patients diagnosed with ENS with those of a control group would also be a useful addition, in our opinion.

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AUTHOR CONTRIBUTIONS

A.R. designed the study and performed experiments and T.D. performed the statistical analysis.

COMPETING INTERESTS

A.R. is the author of enstips.com, provides a fluid simulation service, and sells nasal prostheses for people suffering from Empty Nose Syndrome. Apart from this, authors declare no conflicts of interest.