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Nasal Septal Perforations: A Computational Fluid Dynamics Comparison of Symptomatic and Asymptomatic Patients

Tiago Chantre[1*], Rui Oliveira[2] , Inês Moreira[1], Herédio Sousa[1]

1. Department of Otorhinolaryngology, Lisbon Central University Hospital, Lisbon, Portugal
2. Department of Mechanical Engineering, University of Oporto, Oporto, Portugal

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Corresponding Authors:

Dr. Tiago Filipe Mendes Chantre

Email:
tiagomendeschantre@gmail.com

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Abstract

Background: Computational fluid dynamics (CFD) technology has emerged as a valuable tool for studying nasal physiology.

Aim: The objective of this study was to establish a CFD analysis comparing patients with asymptomatic and symptomatic nasal septal perforations (NSP).

Methods: We applied CFD technology to examine the nasal airflow differences between 10 asymptomatic and 10 symptomatic NSP adult patients. Questionnaires (22-item Sino-Nasal Outcome Test and Nasal Obstruction Symptom Evaluation) were obtained to confirm patients' symptoms.

Results: The asymptomatic NSP group consisted of 4 males and 6 females with a mean age of 46.2 years. The symptomatic group consisted of 5 males and 5 females with a mean age of 42.1 years. The NSP etiology was before nasal surgery in most of the patients (11 cases, 55%). NSPs were considered idiopathic in 3 cases (15%). No statistically significant differences were found between groups regarding sex, age, or etiology of perforation. No statistical differences were found in perforation shape, location, axial diameters, area, nasal resistance, or volumetric flow rate shunting across the perforation between asymptomatic and symptomatic patients. Symptomatic patients had higher wall shear stress along the posterior perforation margins, although the difference was not statistically significant.

Conclusion: NSP altered the physiology of the nasal cavity both in symptomatic and asymptomatic patients. High wall shear stress in posterior perforation regions may explain the crusting most commonly found on posterior NSP margins.

Conflicts of Interest: The Authors declare no conflicts of interest.

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Introduction

Nasal septal perforations (NSP) correspond to an anatomical defect in the nasal septum. Its prevalence is not completely known, but it is believed to be close to 1% of the adult population (1,2). This number rises to 5% in patients undergoing septoplasty (3). In addition to nasal surgery, other risk factors for the development of NSP include trauma with the development of septal hematoma, use of topical nasal therapy (eg, abuse of vasoconstrictors), or toxophilite (eg, cocaine). Perforations can also result from infections, and inflammatory or neoplastic diseases (4). In almost half of the patients, NSP is idiopathic (5). Some patients with NSP remain asymptomatic, while others (60%) have frustrating symptoms including nasal obstruction, dryness, nasal crusting, nasal bleeding, and breathing difficulty (4). The reason why certain perforations are asymptomatic is unclear. Previous clinical observations described that more anteriorly located perforations have a higher incidence of

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shunting airflow through the NSP toward the lower resistance side of the nasal cavity, which could result in a sensation of nasal obstruction or stress injury to the mucosa (6). On the other hand, there are surgeries, such as transsphenoidal approaches to the pituitary, that involve resection of posterior portions of the nasal septum with no apparent symptomatic consequences to the patient.6 Other studies suggested that the location of a septal perforation had no impact on the flow pattern (7). Posterior septectomy has been tried as a treatment with some degree of success especially for large perforations (>2 cm) (8-9).

The geometry of the nasal cavity significantly influences the aerodynamic behavior of airflow and, therefore, affects nasal physiology (10). In recent years, computational fluid mechanics (CFD) technology has asserted itself as a noninvasive tool for quantitative assessment of airflow parameters. Through 3-dimensional (3-D) reconstructions of the nasal cavities created from Computed Tomography (CT) or Magnetic Resonance Imaging (MRI), volumetric flow rate, nasal resistance, velocity distribution, pressure, wall shear stress (WSS) or heat flow can be analyzed. Most previous CFD studies on NSP only studied virtual perforations of non-NSP patients or involved a single NSP model, which impaired the ability to co-relate CFD findings to patients' symptoms (10-12).

This study aims to analyze the impact of NSP on nasal physiology through the application of CFD technology. We examined and compared the nasal airflow characteristics of asymptomatic and symptomatic patients with NSP.

Methods

Patient Selection

A total of 20 patients with NSP were included in this study, with 10 being asymptomatic (Group 1) and 10 being symptomatic (Group 2). All participants had previously undergone a CT scan of the paranasal sinuses to confirm the presence of NSP, and the diagnosis was further confirmed through nasal endoscopy. Informed consent was obtained from all participants, and only adult patients were enrolled. Patients with two or more instances of NSP were excluded from the study.

Patients were asked to complete medical history questionnaires, including a 22-item Sino-Nasal Outcome Test (SNOT-22). (13) and a Nasal Obstruction Symptom Evaluation (NOSE) (14). These questionnaires have been validated for the Portuguese language. The study underwent review and was approved by the Lisbon Central University Hospital Ethics Committee (1248/2022_CA3043.22).

CFD model

The CT scans were imported into CFD software Flowgy© from Spain, which can create a 3D model of the nasal airway using 2D images. A simulation was created for each model with a constant pressure drop between the atmosphere and the nasopharynx to mimic breathing. The volumetric flow rate was kept below 15 L/min to ensure laminar flow, and the model was defined as a rigid body to ignore the effect of soft tissue deformation caused by breathing. The outside temperature was set to 20ºC, and the nasal cavity temperature was set to 37ºC.

Since most nasal septal perforations (NSP) are not perfect circles, the major vertical and horizontal axial diameters of each NSP were measured, and the cross-sectional area of the NSP was calculated. The approximate shape of the perforations was classified as rounded or ovoid. To account for individual differences in nasal cavity size, the NSP locations were normalized using the areas defined by Cottle. Only patients with perforations approximately in the midline were selected to allow for a better comparison of the results.

Six coronal planes were used to analyze the temperature, pressure, wall shear stress (WSS), and velocity contours throughout the nasal cavities. The margins of the perforations for all NSPs were isolated for further analysis. These margins were divided into four zones (anterior, posterior, cranial, and caudal), and the WSS in

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each zone was measured. Nasal cavity resistance and volumetric flow rate were also analyzed.

Statistical Analysis

2-tailed independent-sample t-tests without assuming equal variance were used to compare the asymptomatic and symptomatic groups. Continuous variables were presented as mean and standard deviation (SD), while categorical variables were shown as frequency and percent. All statistical analyses were performed using SPSS version 25 (Statistical Package for the Social Sciences; SPSS Inc., Chicago, IL). Statistical significance was considered at $p<0.05$.

Results

Clinical characteristics

The group with asymptomatic NSP (Group 1) consisted of 10 patients, 4 males, and 6 females. Their ages ranged from 27 to 74 years with a mean of 46.2 ± 15.8 years. The symptomatic group (Group 2) consisted of 10 patients (5 males and 5 females) with ages ranging from 30 to 71 years and a mean of 42.1 ± 15.5 years. Table 1 summarizes the demographic information of all cases studied and compares the groups. No statistically significant differences were found between groups regarding the sex or age of patients (p = 0.653 and p = 0.565, respectively).

Table 1. Demographics of Patients with Asymptomatic Nasal Septal Perforations (Group 1) and Symptomatic Nasal Septal Perforation (Group 2). [a]

Demographics	Group 1 (NSP asymptomatic)	Group 2 (NSP symptomatic)	p value
Patients	10 (100)	10 (100)	
Sex			
Male	4 (40)	5 (50)	0.653
Female	6 (60)	5 (50)	
Age, years	46.2 ± 15.8	42.1 ± 15.5	0.565
Etiology			
Prior Nasal Surgery	5 (50)	6 (60)	0.779
Drug use	2 (20)	1 (10)	
Trauma	1 (10)	2 (20)	
Idiopathic	2 (20)	1 (10)	
SNOT-22	17.9 ± 5.1	58.4 ± 18.3	0.0001
NOSE	22.5 ± 6.5	62 ± 12	0.0001

[a]Values are presented as frequency and percent or mean ± standard deviation. NSP = Nasal Septal Perforation; SNOT-22 = 22-item Sino-Nasal Outcome Test; NOSE = Nasal Obstruction Symptom Evaluation.

The majority of patients with NSP had a history of prior nasal surgery, with 5 out of 10 asymptomatic patients and 6 out of 10 symptomatic patients being affected. In 3 cases, NSP was linked to drug use (2 asymptomatic, 1 symptomatic), and in 3 other cases, it was attributed to trauma (1 asymptomatic, 2 symptomatic). NSP was considered idiopathic in 3 cases (2 asymptomatic, 1 symptomatic). There were no significant differences in the etiology of perforations between the groups (p = 0.779). Patients in Group 1 had significantly lower SNOT-22 scores (17.9 ± 5.1 for asymptomatic, 58.4 ± 18.3 for symptomatic; p = 0.0001) and NOSE scores (22.5 ± 6.5 for asymptomatic, 62 ± 12 for symptomatic; p =

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0.0001) compared to those in Group 2. No nasal crusts were observed during the clinical evaluation of asymptomatic patients. In terms of the shape of NSP, most of the perforations studied were ovoid (6 asymptomatic, 7 symptomatic), and approximately round perforations occurred in 7 patients (4 asymptomatic, 3 symptomatic). There was no significant relationship between perforation shape and the presence of symptoms (p = 0.6392). The majority of nasal perforations were found in areas 2 (3 asymptomatic, 4 symptomatic) and 3 (5 asymptomatic, 4 symptomatic) of Cottle. There was no preferential area associated with the presence of symptoms, and no significant relationship between the location of the perforations and the distribution of patients between groups (p = 0.842). The vertical diameter of NSP was larger in the asymptomatic group (11.26 ± 8.79 mm) than in the symptomatic group (9.06 ± 4.27 mm), but the difference was not statistically significant (p = 0.487). Additionally, the asymptomatic group had a larger horizontal diameter (13.9 ± 9.26 mm) compared to the symptomatic group (10.65 ± 4.61 mm), but this difference was also not statistically significant (p = 0.334). Figure 1 provides a quantitative comparison of the axial diameters of NSP between groups.

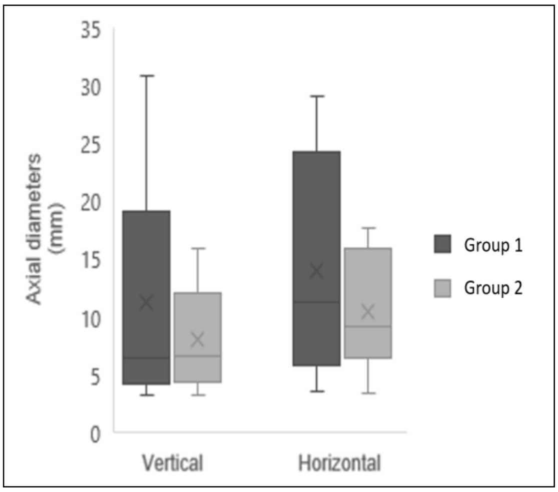

Figure 1. Comparison of the Nasal Septal Perforations (NSP) vertical and horizontal axial diameters (mm) between the asymptomatic (Group 1) and symptomatic (Group 2) patients.

The asymptomatic group had a larger NSP area (187.25 ± 219.31 mm2) compared to the symptomatic group (75.43 ± 60.55 mm2), but the difference was not statistically significant (p = 0.1375). Figure 2 shows a comparison of the cross-sectional area (mm2) between the two groups. In the asymptomatic NSP (Group 1), a maximum vertical diameter of 30.8 mm, a maximum horizontal diameter of 29.1 mm, and a maximum cross-sectional area of 576.6 mm2 were observed. In the symptomatic NSP (Group 2), the maximum vertical diameter was 15.9 mm, the maximum horizontal diameter was 17.6 mm, and the maximum cross-sectional area was 201.6 mm2.

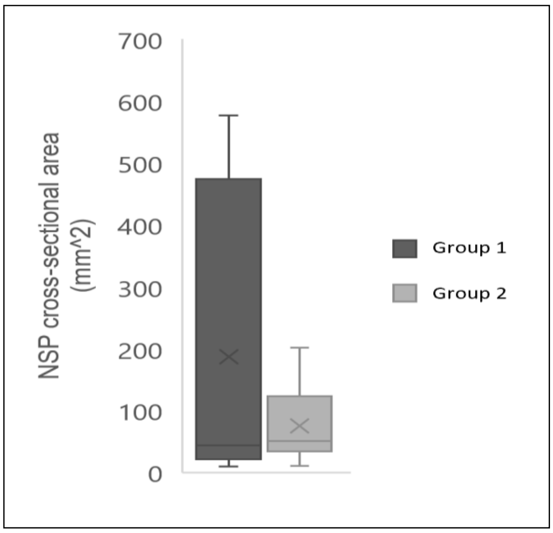

Figure 2. Comparison of the Nasal Septal Perforations (NSP) cross-sectional area (mm^2) between the asymptomatic (Group 1) and symptomatic (Group 2) patients.

The study found that there was no significant difference in nasal resistance between asymptomatic (1.36 ± 0.58 Pa/(L/min)) and symptomatic patients (1.51 ± 0.85 Pa/(L/min)) (p = 0.650). The research also compared various calculated parameters using computational fluid dynamics (CFD) between the two groups. The volumetric flow rate across the perforation was analyzed for each case, and it was observed that there were no statistically significant differences in flow rate between the asymptomatic (1.70± 0.97 L/min) and symptomatic (1.17 ± 1.82 L/min) groups (p =

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0.427). On average, 15.45% and 12.42% of the flow rate in asymptomatic and symptomatic patients, respectively, crosses the perforation, from the nasal cavity with the highest flow to the one with the lowest flow.

Table 2. Comparison of Computational Fluid Dynamics–Calculated Parameters of Patients with Asymptomatic Nasal Septal Perforations (Group 1) and Symptomatic Nasal Septal Perforation (Group 2).[a]

Parameters	Group 1 (NSP asymptomatic)	Group 2 (NSP symptomatic)	p value
Nasal resistance (Pa/(L/min))	1.36 ± 0.58	1.51 ± 0.85	0.650
Volumetric flow rate (L/min)	1.70 ± 0.98	1.17 ± 1.82	0.427
Nasopharyngeal temperature (K)	308.95 ± 0.74	309.12 ± 0.62	0.585

[a]Values are presented as mean ± standard deviation. NSP = Nasal Septal Perforation.

The coronal velocity contour plots show that the highest velocity values were found in the back of the nasopharynx (NSP), while the lowest values were found in the front, for both groups. The heat flux pattern reflects the airflow velocity, with greater heat exchange in the back of the NSP. The nasopharyngeal temperature in asymptomatic patients (308.95 ± 0.74 K) was not significantly different from symptomatic patients (309.12 ± 0.62 K) (p = 0.585**).**

The perforation margins were divided into four regions (anterior, posterior, cranial, and caudal). Similar to velocity and heat flux, coronal contour plots reveal a high WSS peak around the back edges for both asymptomatic and symptomatic NSP. Figure 3 compares the WSS distribution along the NSP margins of two patients (one asymptomatic and one symptomatic) with perforations of similar shape (approximately round) and location (area 3). Both patients have similar WSS distributions, but in the symptomatic perforation (Group 2), the values were higher.

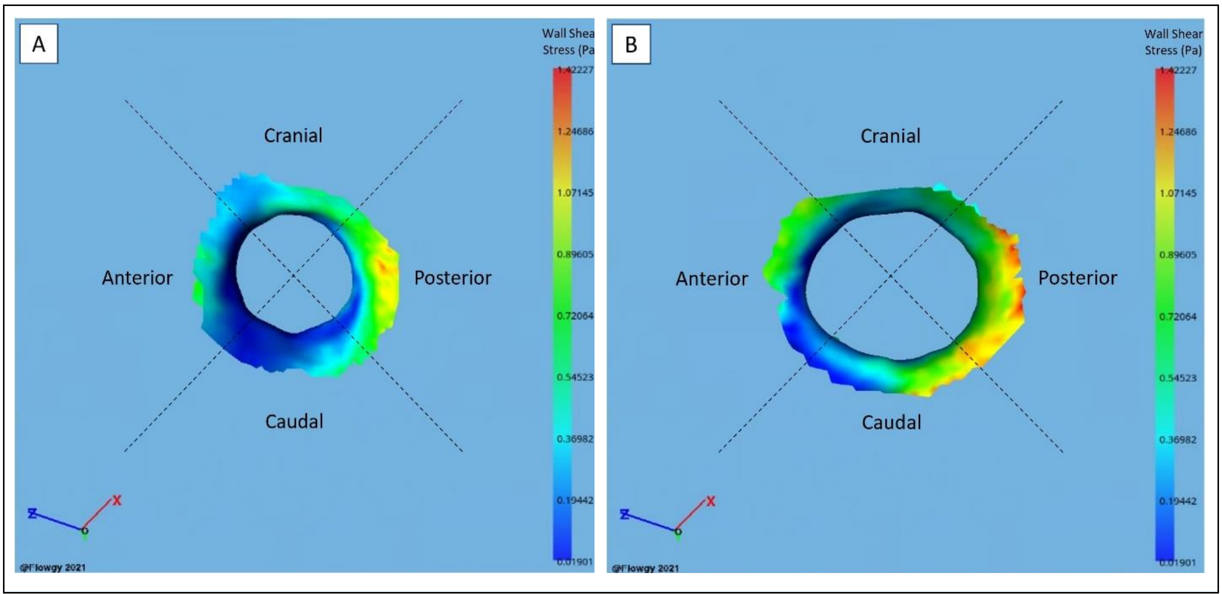

Figure 3. Comparison of the Wall Shear Stress (WSS) distribution along the Nasal Septal Perforations (NSP) margins of 2 patients with perforations of similar location. (A) - Asymptomatic patient (Group 1); B - Symptomatic patient (Group 2).

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Quantitative analysis of WSS in the NSP margins showed that asymptomatic patients (1.09 ± 0.37 Pa) had lower peak WSS than symptomatic patients (0.81 ± 0.22 Pa) in the posterior margins, but the difference was not statistically significant ($p = 0.054$).

Discussion

Previous CFD studies hypothesized that more anterior-located NSPs were more symptomatic due to the increased likelihood of distorted nasal airflow patterns crossing the perforation. Cannon et al. (6) analyzed the influence of perforation size (1 cm and 2 cm) and location (anterior, superior, and posterior) by virtually creating NSP on a healthy nose model. This study showed that for anteriorly located NSP, an increase in size leads to an increase in air crossing the perforation. For posteriorly located NSP, a decrease in perforation size leads to an increase in air crossing the perforation. Our results suggest that symptomatic patients cannot be distinguished from asymptomatic patients by location and size of perforations. Burgos et al. (16) evaluated the location effects of NSP using CFD models created by virtual surgery (2 patients with healthy noses and 2 patients with nasal obstruction). Their study demonstrated that induced NSP only rendered significant flow alterations in noses with preexisting nasal airway obstruction alterations. These studies analyzed changes in purely circular perforations, but perforations are more commonly ovoid in shape as demonstrated in our study (17). In a more recent study, Farzal et al. (17) suggested that round NSP consistently had greater WSS, heat, and water vapor flux compared to their corresponding size oval NSP. In our study, no statistical differences were found regarding the shape of the perforations. The authors also hypothesized that high WSS, heat, and water vapor flux in posterior perforation regions may explain the crusting most commonly noted on posterior NSP edges.

Our CFD measurements showed that there were no statistical differences between the asymptomatic and symptomatic NSP in shape, location, axial diameters, area, nasal resistance, or volumetric flow rate shunting across the perforation. Li et al. (18) performed the only CFD comparative examination of asymptomatic and symptomatic NSP available in the literature. The authors' conclusions were similar to ours. However, their study concluded that symptomatic patients had significantly higher WSS and heat flux, especially along the posterior perforation margin. Our simulation results do confirm that symptomatic NSPs have a significantly higher peak WSS along the posterior perforation margin, but the results were not statistically significant .

As shown in Figure 3, a small and approximately round NSP of area 3 according to Cottle can be either asymptomatic or symptomatic. Although both perforations present intense peaks of WSS in the posterior margins, in the symptomatic perforation the values were higher. Grant et al. (19) demonstrated that a high level of WSS concentrated at the posterior area of the perforation was a predisposing factor for bleeding. In addition, Li et al. (18) hypothesized that the high peaks of WSS and heat flux in the posterior margins of perforations were the indication of an excessively intense air-mucosal interaction that may cause significant drying on the mucosa in that area and produce symptoms such as crusting and bleeding. These findings may support the NSP enlargement with posterior septectomy proposed by Beckmann et al. (9) and Otto et al. (8), because may remove the regional high-stress points along the posterior margin of perforations .

Due to the limited sample size in this study, we did not take into consideration the obstructive effect of anatomic variations such as septal deviation, inferior turbinate hypertrophy, or concha bullosa in the airflow patterns. Some other limitations of this study include the fact that all patients were caucasian and the fact that

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the CFD simulations were done under normal breathing flow rate. The criteria to distinguish symptomatic from asymptomatic NSPs may vary under different breathing conditions. Our simulations also did not consider the effect of the nasal cycle.

In further studies, it would be desirable to include a bigger cohort of patients which could allow us to take into consideration the impact of different anatomic variations or analyze patients after surgical treatment of NSP.

Conclusion

Our study demonstrates the pathological impact of NSP on nasal airflow patterns. High WSS in posterior perforation regions may explain the crusting most commonly noted on posterior NSP margins. Our findings serve as an advance of the CFD use to objectively correlate NSP with symptoms.

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None to declare.

Conflicts of Interest

The authors declare no conflicts of interest.

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Ethics

The study was approved by Lisbon Central University Hospital Ethics Committee (1248/2022_CA3043.22).

Author's contribution

Tiago Chantre, Designed the work, drafted, revised and approved manuscript, accountable for all aspect of the work. Rui Oliveira, Data collection and analysis. Inês Moreira e Herédio Sousa, Drafted, revised and approved manuscript.

Authors ORCIDs

Tiago Filipe Mendes Chantre
https://orcid.org/0000-0002-0217-0981

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