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ORIGINAL ARTICLE

Correlations between computational fluid dynamics and clinical evaluation of nasal airway obstruction due to septal deviation: An observational study

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Abstract

Objectives: The primary objective of this study was to determine how computational fluid dynamics (CFD) could be correlated to clinical evaluation of nasal airway obstruction (NAO) in a population of patients with symptomatic septal deviation (SD). The secondary objective was to determine whether CFD could define which side was the more obstructed.

Design: This was an observational study.

Settings: Few publications have attempted to correlate CFD with clinical evaluation of NAO. This correlation would permit validation and improved interpretation. This study was performed in a university research laboratory specialised in fluid mechanics.

Participants: We included patients referred for septal surgery at our centre. Age range was 19–58 years. Preoperative CT scans were performed. All patients with non-structural causes of NAO such as rhinitis, sinusitis or tumoral/autoimmune processes (ie, not due to anatomic obstruction) were excluded.

Main outcome measurement: For each nasal fossa, we compared CFD data (total pressure, heat flux, wall shear stress, temperatures, velocity and nasal resistances) with both patient perception scores and rhinomanometry using the Spearman correlation test (r_s). Perception scores were graded from 0/4 to 4/4 on each side, based on the patient interview. We also compared CFD-derived nasal resistances with rhinomanometry-derived nasal resistances.

Results: Twenty-two patients complaining of NAO with SD were analysed, and 44 analyses were performed comparing each side with its CFD data. Regarding correlations with patient perception scores, the best values we found were heat flux measures ($r_s = 0.86$). Both rhinomanometry and CFD-calculated nasal resistances had strong correlations with subjective perception scores ($r_s = 0.75$, $P < 0.001$ and $r_s = 0.6$, $P < 0.001$, respectively). We found a statistically significant difference between RMM-NR and CFD-NR ($P = 0.003$). Heat flux analysis allowed us to distinguish the more obstructed side (MOS) and the less obstructed side (LOS) in 100% of patients.

Conclusion: This study aimed to enhance our ability to interpret CFD-calculated data in the nasal airway. It highlights and confirms that heat flux measures are very closely

correlated to patient perception in cases of SD. It also helps to distinguish the more obstructed side from the less obstructed side and could contribute to further CFD studies.

1 | INTRODUCTION

Nasal airway obstruction (NAO) is a common symptom leading many patients to seek a medical consultation and occasionally undergo surgical procedures.¹ Septal deviation (SD) is one of the main causes of NAO.²

Clinical evaluation of NAO is usually carried out by patient interview, self-questionnaires and various physical tests designed to quantify NAO.³ Anterior active rhinomanometry is a physical test performed in many centres to calculate resistance to the airflow in the nasal cavity.⁴

Computational fluid dynamics (CFD) is a recent tool for modelling the nasal cavity as well as for analysing air conditioning and airflow.⁵ Over the past 10 years, more and more authors have assessed the nasal airway using CFD.⁶ New measurements, such as heat flux (HF) and wall shear stress (WSS), are computable by CFD in addition to usual data such as nasal resistances.⁷

However, only a few publications have attempted to correlate CFD with clinical evaluation of NAO and these studies were usually based on a limited number of cases or on healthy subjects.^{6,8} In our view, the correlation between CFD and clinical evaluation of NAO (patient perception and rhinomanometry) would permit validation and improved interpretation. Regarding NAO, patients often complain of unilateral impairment. This is convenient for correlating CFD data as they can be easily calculated on each side: the more obstructed side (MOS) and the less obstructed side (LOS). However, the most frequently used self-questionnaires are quality-of-life evaluation tools, which is why they do not investigate lateralisation of the functional impairment, thus making it difficult to correlate them with CFD-calculated data.³

The primary objective of this study was to determine how CFD could be correlated to clinical evaluation of NAO in a population of patients with symptomatic SD. To do so, we researched the correlations between CFD and patient perception on one hand, and CFD and rhinomanometric data on the other for each of the nasal cavities.

The secondary objective of the study was to determine whether CFD could define which side was the MOS and the LOS.

2 | METHODS

2.1 | Ethical standards

All patients gave written consent before participating in the study, which was conducted according to the Declaration of Helsinki. Authorisation to conduct this study was obtained from the Ethical Committee of our institution (Assistance Publique des Hôpitaux de Marseille, N°2017-14-12-005).

Keypoints

- Septal deviation is one of the main causes of nasal airway obstruction.
- Computational fluid dynamics is a recent tool for modelling the nasal cavity as well as for analysing air conditioning and airflow. Thanks to developments and technical progress in recent years, it is now possible to perform computational fluid dynamics on the nasal airway.
- The correlation between computational fluid dynamics and clinical evaluation of nasal airway obstruction would permit validation and improved interpretation.
- This study aims to enhance our ability to interpret CFD-calculated data in the nasal airway. It highlights and confirms that heat flux measures are very closely correlated to patient perception in cases of SD.
- We found that CFD-computed nasal resistances were strongly correlated with patient perception. However, CFD-calculated nasal resistances had low correlations with rhinomanometry in our series.

2.2 | Patient selection

All patients were referred for septal surgery at our centre between January 2017 and September 2018. Age range was 19–58 years (mean 37 years). Preoperative CT scans were obtained using a low dose protocol on a multi-detector CT scanner (Aquilion Prime, Canon Medical Systems) using a cranio-caudal helical acquisition. Fixed parameters were used in accordance with the industrial engineer: 80×0.5 mm detectors, FOV: extra-small 180 mm, 40 mm collimation, 0.5 seconds revolution time, pitch of 0.625 mm/rotation, 100 kV tube voltage, DPL target of 50 mGy cm, scout view auto-exposure of mAs intensity, FC30 bone filter, Adaptive Iterative Dose Reduction-3D standard reconstruction. Voxel dimensions were $0.35 \times 0.35 \times 0.5$ mm (0.61 mm^3).

2.3 | Exclusions

All patients with non-structural causes of NAO such as rhinitis, sinusitis or tumoral/autoimmune processes (ie, not due to anatomic obstruction) were excluded. We excluded patients presenting symptoms alternating from one side to the other as this can create bias, especially regarding CFD-NR.⁹ We also excluded patients with the same perception score on both sides, in order to clinically determine a MOS and a LOS for each patient.

FIGURE 1 Example of CT scan in axial and coronal view showing where CFD data were calculated on the more obstructed side. P1 = 0 Pa and T1 = 19°C for every patient. HF, Heat Flux; T, Temperature; TP, Total Pressure; WSS, Wall Shear Stress

2.4 | Clinical evaluation of NAO

2.4.1 | Patient perception scores

In all patients, subjective perception of nasal airflow was quantified separately on each nasal cavity: 0 = "no obstruction," 1 = "slight obstruction," 2 = "moderate obstruction," 3 = "severe obstruction" and 4 = "total obstruction." The more obstructed side was abbreviated to MOS. The less obstructed side was abbreviated to LOS. The definition of the LOS and MOS was based on the subjective scores. Clinical evaluation was performed 1 month before surgery, in the absence of any intercurrent infectious episode.

2.4.2 | Rhinomanometry

Anterior active rhinomanometry (without vasoconstriction) was performed before surgery. No procedures (eg, Cottle or Bachman tests) were performed in order to avoid deforming the nasal anatomy. The same rhinomanometer was used for all patients (Otopront® Rhinon-sys®

Happersberger Otopront GmbH 2008). Right and left nasal resistances were calculated. Nasal resistances obtained using rhinomanometry were measured at a pressure drop of 150 Pa and are abbreviated to RMM-NR

2.5 | Creation of 3-dimensional models

3D reconstructions were obtained using ITK-SNAP (3.6.0). The procedure was as follows: (a) importation of CT scan images (DICOM formats), (b) segmentation process using the half-maximum height protocol (IMAGEJ software version 1.44o) to determine the boundaries of anatomical structures and (c) nasal surface extraction. No smoothing algorithm was applied. The half-maximum height protocol offers an objective process to delimit a reproducible interface between two tissues.¹⁰ This method included pixels from -1024 to -400 Hounsfield Units. Paranasal sinuses were removed manually during the segmentation process.

2.6 | CFD protocol

CFD was performed using STAR-CCM+® software (CD-ADAPCO-www.cd-adpaco.com). The computational domain was the Boolean union of extracted surface and a 3 cm-diameter sphere centred on the tip of the nose. The aim of this sphere was to impose a pressure boundary condition far from the nostrils, thus allowing a non-imposed air-flow close to the nasal entrance.

TABLE 1 Correlations of CFD data with patient perception

	r_s	95% CI	P
Total pressure			
P2	0.31	0.12; 0.64	0.041
P3	-0.47	-0.77; -0.38	0.001*
P4	-0.33	-0.6; -0.1	0.002*
P5	-0.02	-0.34; 0.38	0.89
Heat flux			
HF1	0.51 ^a	0.32; 0.77	<0.001*
HF2	0.65 ^a	0.47; 0.81	<0.001*
HF3	0.86 ^b	0.57; 0.91	<0.001*
HF4	0.71 ^a	0.44; 0.83	<0.001*
Temperature			
T2	0.53 ^a	0.34; 0.76	<0.001*
T3	0.44	0.13; 0.70	0.003*
Velocity			
Vmax	0.26	0.04; 0.76	0.11
Wall shear stress			
WSS1	0.05	-0.28; 0.38	0.75
WSS2	0.52 ^a	0.32; 0.77	<0.001 ^c

Note: HF3 had the best match with patient perception. r_s = Spearman correlation test.

^aStrong correlations.

^bVery strong correlations.

^cSignificant results ($P < 0.004$ after Bonferroni correction).

FIGURE 2 Lateral views of MOS (Right side) and LOS (Left side) according to (A) total pressure (Pa), (B) heat flux (W/m²), (C) wall shear stress (Pa) and (D) streamlines. Streamlines are coloured according to total pressure. The patient complained of right side “Total Obstruction” (4/4). On the left side, he reported “No obstruction” (0/4). On the MOS, we observed a strong Pressure drop and decreased Heat Flux. WSS1 and 2 were null and lower, respectively, on the MOS

Volume mesh was performed using a polyhedral mesher with parameters defined after a convergence mesh study: the prism layer (total thickness = 0.16 mm) included 10 prismatic cells with 1.1 prism layer stretching ratio.

We defined the following computational hypothesis: airflow to standard conditions for temperature (19°C) and atmospheric pressure (101 325 Pa). Air was considered to be an incompressible Newtonian fluid with density $\rho = 1.225 \text{ kg/m}^3$ and viscosity $\mu = 1.8 \times 10^{-5} \text{ Pa seconds}$.

We considered the flow to be laminar. Steady computation was used, with a segregated solver and second-order accuracy in space. Sinonasal surface was a non-slip wall. Wall temperature was 34°C.¹¹ An imposed atmospheric pressure (reference value) was defined on the sphere surface (101 325 Pa). We analysed total pressure (TP) where TP = static pressure + dynamic pressure. Nasopharynx was a pressure outlet with an imposed pressure. In case of re-entry, the temperature of air in the nasopharynx was 37°C. The differential pressure imposed in the nasopharynx was -150 Pa. CFD-calculated nasal resistances were called CFD-NR. CFD-NR were calculated for the right and left side. Nasal resistances were expressed as $R = \Delta P/V$, where ΔP is the pressure differential between the nostril and the rhinopharynx and V is the airflow rate, expressed in Pa s/mL. The pressure drop used to compute nasal resistance was total pressure differential.

A total of 30 CFD variables were collected for each patient, 15 on each side (Figure 1):

All measurements in axial view were performed 1.5 cm from the nasal floor on the septal wall. Total pressure, heat flux and WSS were measurement averages within a circular wall region of 1 cm². P1, P2, P3, P4 and P5 were the pressure differentials with respect to atmospheric pressure. Pressures were measured in the ambient air (atmospheric pressure = 101 325 Pa, P1 = 0 Pa), 0.1 cm before the junction between upper lateral and lower lateral cartilages (nasal valve area; P2), 1 cm after maximum SD on MOS (or symmetrically for LOS; P3), 2 cm before the choana (the posterior third of the nasal septum; P4) and at the choana (P5). Heat flux (ie, the rate of heat transfer across a surface per unit of time and area) was measured at the entrance to the nose (1 cm before the junction between upper lateral and lower lateral cartilages, on the nostril side; HF1), 0.1 cm before the junction between upper lateral and lower lateral cartilages (nasal valve area; HF2), 1 cm after maximum SD on MOS (or symmetrically for LOS; HF3) and 2 cm before the choana (posterior third of the nasal septum; HF4). Average HF measures were mean HF values calculated for both sides.

WSS was measured 0.1 cm before the junction between upper lateral and lower lateral cartilages (nasal valve area; WSS1) and at the maximum SD, depending on patient's deviation (WSS2).

Maximum velocity was assessed for each nasal fossa (Vmax). Temperatures were recorded in ambient air (T1), in the middle meatus (after the SD for MOS, symmetrically for LOS; T2) and at the choana (T3).

2.7 | Statistical analyses

Results were analysed using Microsoft Office Excel. Statistical calculations were performed using PAST software (Oyvind Hammer, University of Oslo, Norway). To compare CFD-NR and RMM-NR, statistical differences were assessed using a paired t test. Comparisons between NAO and CFD variables were made using the Spearman correlation test (r_s). The correlation was considered perfect if $|r_s| = 1$, very strong if $|r_s| > 0.8$, strong if $0.5 > |r_s| > 0.8$, moderate if $0.2 > |r_s| > 0.5$, low if $|r_s| < 0.2$ and null if $r_s = 0$. The 95% confidence intervals of Spearman's rank correlation coefficients were computed by bootstrapping using the RVAideMemoire package for R3.5 (R Foundation for Statistical Computing). Comparisons between nasal cavity MOS and LOS were made using paired Wilcoxon test. P values < 0.004 were considered to be statistically significant after Bonferroni correction. Pearson correlation coefficient was used to compare RMM-NR and CFD-NR.

3 | RESULTS

3.1 | Population

We selected 22 patients complaining of NAO with SD. Most of them had an anterior SD. We were thus able to perform 44 analyses comparing each side with its CFD data. Regarding patient perception scores, we found for MOS a severe obstruction score (mean score $\pm$ standard deviation = 3.18 ± 0.80); For LOS, we found a low obstruction score (mean score $\pm$ standard deviation = 0.95 ± 0.79). The difference between MOS and LOS was statistically significant ($P < 0.001$).

3.2 | Correlation of CFD with subjective perception of nasal airflow

3.2.1 | Pressures, heat flux, temperatures, velocities, wall shear stress

Regarding correlations with patient perception, we found a very strong correlation for heat flux values after SD (HF3; Figures S2 and S3; Table 1). We also found a strong correlation with all other HF values, T2 and WSS2. Moderate correlations were found for P2, P3, P4, T3 and Vmax. Correlations were low or non-significant for P5, WSS1 and Vmax. After Bonferroni correction, only P2 became non-significant ($P > 0.004$).

3.2.2 | RMM-NR and CFD-NR

Both RMM-NR and CFD-NR had strong correlations with subjective scores ($r_s = 0.75$, $P < 0.001$ and $r_s = 0.6$, $P < 0.001$, respectively).

FIGURE 3 A, Temperatures (°C) and (B) velocities (m/s). in axial view for the same patient (Right-side obstruction). Temperatures were lower in the LOS. However, velocities were higher on the LOS when NAO was total

3.3 | Comparison between MOS and LOS

3.3.1 | Pressures, heat fluxes, temperatures, velocities, wall shear stress

Regarding total pressure, we found a big pressure drop after SD (P3) in MOS (Figures 2, 3, and 4A; Table 23.1; Video S1). The difference was statistically significant comparing MOS and LOS for P3 ($P < 0.001$). However, we found no statistically significant differences for P2, P4 and P5. There was a strong modification of HF, moving closer to 0 W/m², after SD on MOS (HF3, Figure 4B).

The difference was statistically significant comparing MOS and LOS for HF1, HF2, HF3 and HF4 ($P < 0.001$). Average heat flux measures in LOS were higher than MOS thus allowing us to identify LOS and MOS in 100% of patients. At T2 (Figure 4C), mean temperatures were $28.5 \pm 3.6^\circ\text{C}$ and $23.3 \pm 2.8^\circ\text{C}$, respectively, for MOS and LOS. At T3, mean temperatures were $30.9 \pm 1.9^\circ\text{C}$ and $29 \pm 2.3^\circ\text{C}$, respectively, for MOS and LOS. Differences were statistically significant at T2 between MOS and LOS ($P < 0.001$). We also found a strong correlation between HF and temperatures ($r_s = 0.56$, $P < 0.001$). Maximum velocities were higher on MOS. The difference between MOS and LOS was not statistically significant ($P = 0.039$). Comparing WSS, they were statistically higher on MOS in WSS2 values but not in WSS1 ($P = 0.065$; Figure 4D).

3.3.2 | RMM-NR and CFD-NR

RMM-NR were mean 1.8 ± 2.2 Pa s/mL for MOS. RMM-NR were mean 0.6 ± 0.37 Pa s/mL for LOS ($P = 0.01$). CFD-NR were mean 0.8 ± 1.17 Pa s/mL for MOS. CFD-NR were mean 0.23 ± 0.1 Pa s/mL for LOS ($P = 0.03$).

We found a statistically significant difference between RMM-NR and CFD-NR ($P = 0.003$, Figure S1). The Pearson correlation coefficient was $r = 0.145$ ($P = 0.3$) between RMM-NR and CFD-NR. RMM-NR in LOS were lower than MOS in 91% of analyses. CFD-NR in LOS were lower than MOS in 82% of analyses. CFD-calculated flow rates in LOS were higher than MOS in 82% of analyses.

4 | DISCUSSION

4.1 | Synopsis of new findings

The ability to analyse airflow and air conditioning within the nasal cavities offers new perspectives in rhinology. Over the past 10 years, many CFD studies have investigated the nose, first in healthy or cadaveric subjects, and then in patients.¹²⁻¹⁴ The analysis and interpretation of CFD-calculated data must be correlated with the patient's clinical experience.⁶ To that end, CFD must be compared with already existing tests or examinations, especially relative to new data such as HF or WSS.

4.2 | Clinical applicability of the study

Clinical evaluation of NAO remains difficult. Many tools have been developed in recent years, and patient reported outcome has become more and more important in functional procedures. Evaluation can be performed subjectively, often by self-questionnaires. The NOSE, SNOT-22 and ENS6Q self-questionnaires are the most used in the literature.^{9,14,15} Despite being widely validated in the literature, these questionnaires do not lateralise MOS and LOS although, in most cases, patients with NAO complain more about one side than about the other. Furthermore, CFD analysis is predominantly performed unilaterally.¹⁶ It is not logical, therefore, to compare a

FIGURE 4 Mean values in the cohort of 22 patients: total pressure, heat flux, temperatures and wall shear stress are compared using boxplots according to MOS and LOS. A huge total pressure and heat flux drop (P3, HF3) were found after the septal deviation in MOS

unilateral CFD analysis with a global clinical feeling. For this reason, we found it useful to make separate clinical evaluations of MOS and LOS so as to compare with their CFD data. Establishing the correlation between CFD data and patients' clinical perceptions appears fundamental in order to better interpret CFD. Our study used a convenience sample of patients presenting a septal deviation, without any other cause of nasal involvement. This must be kept in mind when interpreting our results.

4.3 | Comparison with other studies

Kimbell et al^{16,17} and Kim et al¹⁸ also found big changes in airflow characteristics on MOS after SD (Video S1). Similarly for HF, which decreased after SD and was closely correlated with patient perception (Figures 2 and 4). The decrease of HF after SD can be explained by reduced airflow in this area responsible for less heat exchange between cool air (19°C) and mucosa (34°C).

Although there are different ways of measuring HF (Total HF, Peak HF, SAHF50), many authors have found a strong correspondence between HF and patient perception,^{17,19,20} whatever the method adopted. We also noted this strong correlation. This finding reinforces the idea that the mucosal cooling effect plays a large part in NAO perception, and that the latter is probably multifactorial and not dependent exclusively on nasal resistances as suggested for many years.¹¹ In our study, average heat flux measures were always higher in LOS, thus suggesting that heat flux measures can distinguish MOS from LOS. Since HF is dependent on air and wall temperatures, it is scientifically logical to find a strong correlation between HF and temperatures ($r_s = 0.56$). It is also logical that temperature differences between MOS and LOS are lower at T3 than at T2 as air temperature has nearly achieved the wall temperature in both sides by the time inspired air reaches the choana.

Regarding WSS, there was a good correlation with subjective scores for the WSS2 measured on the maximum SD but not in the

TABLE 2 Comparisons between mean CFD values for more obstructed side and less obstructed side

	MOS	LOS	P
Subjective scores			
	3.18 ± 0.80	0.95 ± 0.79	<0.001*
Total pressure (Pa)			
P2	-34.6 ± 40.0	-42.9 ± 31.8	0.52
P3	-128.5 ± 47.6	-75.4 ± 42.0	0.003*
P4	-114.9 ± 33.7	-99.3 ± 38.5	0.11
P5	-123.6 ± 24.9	-123.8 ± 24.6	0.775
Heat flux (W/m ²)			
HF1	1069 ± 872	2192 ± 867	<0.001*
HF2	731 ± 941	1952 ± 864	0.001*
HF3	153 ± 212	1290 ± 947	<0.001*
HF4	276 ± 308	944 ± 709	<0.001*
Temperature (°C)			
T2	28.5 ± 3.6	23.3 ± 2.8	<0.001*
T3	30.9 ± 1.9	29.0 ± 2.3	0.007
Velocity (m/s)			
Vmax	13.0 ± 4.0	10.2 ± 4.0	0.039
Wall shear stress (Pa)			
WSS1	5.68 ± 6.15	2.54 ± 1.99	0.065
WSS2	7.21 ± 4.78	2.89 ± 2.23	0.002*

Note: P2, P4 and P5 and WSS1 showed no statistical difference between MOS and LOS.

Abbreviations: LOS, Less Obstructed Side; MOS, More Obstructed Side.

*Significant results ($P < 0.004$ after Bonferroni correction).

nasal valve area (WSS1). Kimbell et al¹⁷ reported a correlation with patient perception measuring WSS on the entire MOS.

Regarding velocities, discordant results were found in our series which sometimes displayed higher velocities in LOS.¹³ Moreover, Vmax was poorly correlated with patient perception. Velocity and WSS are very dependent on anatomic variations. These discrepancies for WSS1 and Vmax can be explained by an "ON-OFF" effect in the event of total NAO. Logically, the greater the deviation, the higher the WSS1 and Vmax. However, in the event of absence of airflow due to totally obstructive septal deviation, WSS1 and Vmax are necessarily null and therefore lower in MOS than in LOS (Figure 3).

Nasal resistance is one of the most used data for assessing NAO perception prior to surgery (septoplasty, inferior turbinate hypertrophy or functional rhinoplasty). However, few studies have sought to compare RMM-NR and CFD-NR. Those studies that have been performed analyse only small cohorts or healthy subjects.^{8,21,22} This is the first study to compare CFD-NR and RMM-NR in a large cohort of patients with NAO. While establishing a good correlation between patient perception and both RMM-NR and CFD-NR, the correlation between CFD-NR and RMM-NR was poor ($r = 0.14$) in our series and lower than in Zhao's studies ($r = 0.41$ and $r = 0.53$).^{20,21} However, Zhao analysed only healthy volunteers. In our study, we used total

pressure differential to compute nasal resistance. This can explain in part why CFD-NR was statistically different from RMM-NR. More studies need to be performed on this topic, on larger series, including NAO causes such as inferior turbinate hypertrophies or nasal valve collapses.

Indeed, using a small convenient sample clearly limits the statistical power of our study. Great care is needed when calculating CFD-NR: using a steady flow and a non-deformable model may have an impact on CFD-NR. Moreover, the presence of a strong nasal cycle could bias CFD-NR analysis. Although the inferior turbinates can be reduced by applying vasoconstrictors, this procedure distorts reality. To overcome this problem, Gaberino et al⁹ proposed virtual modelling to correct the nasal cycle: the correlation between CFD-NR and patient perception was greatly increased.

4.4 | Limits

To date, CFD can only analyse static disorders related to nasal ventilation. However, it is well known that ventilatory disorders can be dynamic, especially regarding the nasal valve.²³ These disorders appear only above an airflow threshold involving dynamic nasal valve collapse. To date, CFD in the nasal airway does not assume deformable walls.

We used a steady flow simulating continuous inspiration. This model is quite different from clinical reality.⁴ CFD can calculate these inspiration/expiration cycles, even if the computing times are much longer. Importantly, we analysed inspiratory and not expiratory resistance. This choice was made because, in most cases, patients complain only of impairment due to inspiration. We acknowledge using a small series (in terms of statistical power) and a non-validated perception score. Moreover, patients and assessors were not blinded to the findings. We used a convenience sample subject to selection bias, which is not representative of the global population.

5 | CONCLUSION

This study aimed to enhance our ability to interpret CFD-calculated data in the nasal airway. Despite the small number of patients, this study highlights and confirms that heat flux measures are closely correlated to patient perception in cases of SD. It also helps to distinguish the more obstructed side from the less obstructed side. This should encourage further CFD studies, on larger series, including other NAO causes such as inferior turbinate hypertrophies or nasal valve collapses.

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CONFLICT OF INTEREST

None to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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