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

Running title: CFD and nasal airway

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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 of the study 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.

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).

Results

22 patients complaining of NAO with SD were analyzed, allowing to perform 44 analyses comparing each side with its CFD data. Regarding correlations with patient perception scores, we found the best values for Heat Flux measures. Both clinical and CFD-calculated nasal resistances had strong correlations with nasal impairment.

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.

Keywords: CFD; nasal airway obstruction; surgery; functional; septal deviation; nasal valve; inferior turbinate hypertrophy

INTRODUCTION

Nasal airway obstruction (NAO) is a common symptom leading many patients to seek a medical consultation and occasionally undergo surgical procedures (1)(2). Septal deviation (SD) is one of the main causes of NAO (3).

Clinical evaluation of NAO is usually carried out by patient interview, self-questionnaires and various physical tests designed to quantify NAO (4). Anterior active rhinomanometry is a physical test performed in clinical routine, in many centers, to calculate resistance to the airflow in the nasal cavity (5).

Computational Fluid Dynamics (CFD) is a recent tool for modeling the nasal cavity as well as for analyzing air conditioning and airflow (6). Over the past 10 years, more and more authors have assessed the nasal airway using CFD (7). 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 (8)(9).

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 (7)(10). 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 lateralization of the functional impairment, thus making it difficult to correlate them with CFD-calculated data (11) (12).

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.

METHODS

Ethical standards

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

Patient selection

All patients were referred for septal surgery at our center between January 2017 and September 2018. Age range was 19 to 58 years (mean 37 years). Preoperative CT scans were obtained using 2 CT scanners (Scanner Siemens Somatom definition, Siemens Healthcare, Germany and Scanner General Electric Light speed LS 16 Pro, GE) applying the following parameters: Kv: 120, mAs : 130, 0.3mm slice every 0.6 mm.

All patients with other causes of NAO such as rhinitis, sinusitis or tumoral / autoimmune processes (i.e., not due to anatomic obstruction) were excluded. We also excluded patients presenting symptoms alternating from one side to the other as this can create bias, especially regarding CFD-NR (13).

Clinical evaluation of NAO

Patient perception scores

In all patients, assessment of NAO perception was performed separately for each nasal cavity. Thus, patients were assessed as follows for right and left nasal fossae: 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. NAO perception could be scored 0/4, 1/4, 2/4, 3/4 or 4/4 on each side. Clinical evaluation was performed one month before surgery, in the absence of any intercurrent infectious episode.

Rhinomanometry

Rhinomanometry (without vasoconstriction test) was performed before surgery. No procedures (e.g. 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). The threshold value used to assess the presence of nasal obstruction was 0.30 sPa/mL, as defined by the manufacturer. Resistance between 0.30 and 0.49 sPa/mL denoted mild obstruction, resistance between 0.50 and 0.80 sPa/mL moderate obstruction and resistance greater than 0.80 sPa/mL severe obstruction. Right and left nasal resistances were calculated. Nasal resistances obtained using rhinomanometry are abbreviated to RMM-NR.

Creation of 3-Dimensional Models

3D reconstructions were obtained using ITK-Snap (3.6.0) (14). The procedure was as follows: (1) Importation of CT scan images (DICOM formats) into ITK-Snap, (2) segmentation process using ImageJ (software version 1.44o) to determine the boundaries of anatomical structures, and (3) paranasal sinus surface extraction (15). Some manual corrections were performed when the threshold did not permit identification of thin anatomical structures. No smoothing algorithm was applied. The file containing the sinonasal 3D surface mesh was saved in STL format.

CFD protocol

CFD was performed using Star-CCM+® software (CD-ADAPCO - www.cd-adpaco.com). The procedure for surface preparation was as follows: (1) definition of a new orthonormal XYZ (2), reduction of the computational domain from the nostril to the nasopharynx, (3) definition of the boundary conditions.

Volume meshing of the computational domain was performed using a polyhedral mesher with parameters defined after a convergence mesh study: 10 prismatic layers with elements of 0.25 mm. We defined the following computational hypothesis: airflow to standard conditions for temperature (19°) and atmospheric pressure (101 325 Pa). Air was considered to be a newtonian fluid, incompressible with constant density ($\rho=1.225 \text{ kg/m}^3$) and viscosity $\mu=1.18 \times 10^{-5} \text{ Pa.s}$. Nasal airflow at resting breathing rates has been described as predominantly laminar in healthy individuals; 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 (16). Nostrils were pressure outlets with an imposed atmospheric pressure ($\Delta P=0 \text{ Pa}$). Temperature of inspired air was 19°C. Nasopharynx was a

pressure outlet with an imposed pressure. In case of reentry, 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 $R = \frac{\Delta P}{V}$, where ΔP is the pressure differential between the nostril and the rhinopharynx and V is the airflow rate, expressed in sPa/mL.

A total of 30 CFD-calculated data were collected for each patient, 15 on each side (**Figure 1**):

Total Pressure was measured in the ambient air (P1), before the nasal valve (P2), after SD on MOS (or symmetrically for LOS) (P3), at the posterior third of the nasal septum (P4) and at the choana (P5). Peak Heat flux (i.e. the rate of heat transfer across a surface per unit of time and area and measures of heat loss from the nasal mucosa to the inspired air) was measured in a surface area of 1 cm² at the entry of the nose (HF1), in the nasal valve area (HF2), after SD on MOS (and symmetrically for LOS) (HF3), and in the posterior third of the nasal septum (HF4). WSS was measured in the nasal valve area (WSS1) and at the maximum SD (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).

Statistical analyses

Results were analyzed using Microsoft Office Excel. Statistical calculations were performed using PAST software (Oyvind Hammer, Natural History Museum, 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 values were made using the Spearman correlation test (r_s). The correlation was considered perfect if $r_s = 1$ or -1 , very strong if $r_s > 0.8$ or < -0.8 , strong

if $0.5 > r_s > 0.8$ or $-0.8 < r_s < -0.5$, moderate if $0.2 > r_s > 0.5$ or $-0.5 < r_s < -0.2$, low if $r_s < 0.2$ or > -0.2 and null if $r_s = 0$. Comparisons between nasal cavity MOS and LOS were made using paired Wilcoxon test. p values < 0.05 were considered to be statistically significant.

RESULTS

Population

We selected 22 patients complaining of NAO with 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 SD = 3.13 ± 0.79); For LOS, we found a low obstruction score (mean score \pm SD = 0.95 ± 0.78). The difference between MOS and LOS was statistically significant ($p < 0.05$).

Correlation of CFD with clinical evaluation of NAO

Results are reported in Table 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). 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 for P5 and WSS1.

RMM-NR and CFD-NR

Both RMM-NR and CFD-NR had strong correlations with nasal impairment ($r_s = 0.75$, $p < 0.001$ and $r_s = 0.6$, $p < 0.001$, respectively).

Comparison between MOS and LOS

Results are reported in Table 2.

Pressures, Heat Fluxes, Temperatures, Velocities, Wall Shear Stress (Figures 2 and 3)

Regarding Total Pressure, we found a big pressure drop after SD (P3) in MOS (Figure 4a, Video 1). 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 also a HF drop after SD on MOS (HF3, Figure 4 b). The difference was statistically significant comparing MOS and LOS for HF1, HF2, HF3, and HF4 ($p < 0.001$). At T2 (Figure 4c), mean temperatures were 28.06 ± 3.65 °C and 23.5 ± 2.87 °C, respectively, for MOS and LOS. At T3, mean temperatures were 30.6 ± 1.97 °C and 29.08 ± 2.15 °C, respectively, for MOS and LOS. Differences were statistically significant at T2 and T3 between MOS and LOS ($p < 0.001$ and $p = 0.007$, respectively). 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 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).

RMM-NR and CFD-NR

RMM-NR were mean 1.8 ± 2.2 sPa/mL for MOS. RMM-NR were mean 0.6 ± 0.37 sPa/mL for LOS. The difference was statistically significant ($p = 0.01$). CFD-NR were mean 0.8 ± 1.17 sPa/mL for MOS. CFD-NR were mean 0.23 ± 0.1 sPa/mL for LOS. The difference was statistically significant ($p = 0.03$).

We also found a statistically significant difference between RMM-NR and CFD-NR ($p = 0.003$).

DISCUSSION

Synopsis of new findings

The ability to analyze 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 (17)(18)(19). The analysis and interpretation of CFD-calculated data must be correlated with the patient's clinical experience (7). To that end, CFD must be compared with already existing tests or examinations, especially relative to new data such as HF or WSS.

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 and VAS are the most used in the literature (20)(21)(13). Despite being widely validated in the literature, these questionnaires do not lateralize 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 (22)(23). It is not logical, therefore, to compare a 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.

Comparison with other studies

In most data in the literature, we found a significant pressure drop and a big change in airflow on MOS (24)(25) after surgery (**Video 1**). Similarly for HF, which decreased after SD and was closely correlated with patient perception (Figure 2, 4). 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 (26) (27)(28), 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 (16). 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 temperature is measured at the choana and, in this region, thermal exchanges may occur between MOS and LOS.

Regarding WSS, there was a good correlation for the WSS2 measured on the maximum SD but not in the nasal valve area (WSS1). Kimbell et al. reported a correlation with patient perception measuring HF on the entire MOS (29). In our patient presented in Figure 2c, we did not observe higher WSS in the nasal valve area. From our study, it appears that WSS is very dependent on anatomic variation. Indeed, when no airflow is possible due to severe deviations, WSS corresponding to air friction is inevitably close to 0.

Regarding velocities, discordant results were found in our series which sometimes displayed higher velocities in LOS (18). Moreover, although the difference was statistically significant between MOS and LOS with higher mean velocities in MOS, Vmax was poorly correlated with patient perception. These discrepancies for WSS1 and Vmax can be explained by an "ON-OFF" effect in case of total NAO. Indeed, velocity and WSS are null in the presence of total NAO and

are therefore lower in MOS than in LOS (Figure 3). It is therefore essential to be wary when interpreting statistical analyses of velocities and WSS, which cannot be significant in case of total NAO.

Nasal resistance is one of the most used data for assessing NAO perception prior to surgery (septoplasty, inferior turbinate hypertrophy or functional rhinoplasty). Thanks to developments and technical progress in recent years, it is now possible to calculate CFD-NR. However, few studies have sought to compare RMM-NR and CFD-NR. Those studies that have been performed analyze only small cohorts or healthy subjects (9) (10) (30). Our study found a good correlation between patient perception and both RMM-NR and CFD-NR, thus validating the use of this datum on patients with SD. However, great care is needed when calculating CFD-NR, and different points must be checked to ensure the accuracy of the data obtained. Indeed, the presence of a strong nasal cycle could bias CFD-NR analysis. Although the inferior turbinates can be reduced by applying vasoconstrictors before rhinomanometry, this procedure is often difficult to perform before a CT scan. Whatever the case, the use of vasoconstrictors distorts reality. A better option is to choose patients who do not display a widely varying nasal cycle. To overcome this problem, Gaberino et al. proposed virtual surgery in order to correct the nasal cycle (13). The authors reported that after virtual correction of the nasal cycle, the correlation between CFD-NR and patient perception was greatly increased.

Limits

To date, CFD can only analyze static disorders related to nasal ventilation. However, it is well known that ventilatory disorders can be dynamic, especially regarding the nasal valve, (31). 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 in which a nasal cycle follows a curve, as described by Vogt et al. (5). CFD can calculate these inspiration/expiration cycles, even if the computing times are much longer. Importantly, we analyzed inspiratory and not expiratory resistance. This choice was made because, in most cases, patients complain only of impairment due to inspiration.

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 would be valuable to perform a similar study before and after surgery and compare CFD with changes in patient perception.

	Total pressure				Heat Flux				Temperature		Velocity	Wall Shear Stress	
	P2	P3	P4	P5	HF1*	HF2*	HF3*	HF4*	T2*	T3	Vmax	WSS1	WSS2*
r _s	0.31	-0.47	-0.33	-0.02	0.51	0.65	0.86	0.71	0.53	0.44	0.26	0.05	0.52
p	0.041	0.001	0.002	0.89	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.11	0.75	<0.001

Table 1. Correlations of CFD data with patient perception. HF3 had the best match with patient perception. * marks very strong and strong correlations.

	Clinical evaluation	Total Pressure				Heat Flux				Temperature		Velocity	Wall Shear Stress	
		P2	P3	P4	P5	HF1	HF2	HF3	HF4	T2	T3	Vmax	WSS1	WSS2
MOS	3.18	-34.62	-128.5	-114.91	-123.57	-1069.45	-731.5	-153.86	-276.68	28.47	30.88	13.03	5.68	7.21
±SD	0.8	39,94	47.59	33.73	24.87	872.21	941.72	212.44	308.84	3.56	1.88	4.04	6.15	4.78
LOS	0.95	-42,95	-75.41	-99.27	-123.82	-2192.86	-1952.41	-1290	-944	23.27	28.98	10.17	2.54	2.89
±SD	0.79	31,85	42.03	38.46	24.62	867.57	864.34	947.68	709.33	2.78	2.3	4.02	1.99	2.23
p	<0.001	0,52	0.003	0.11	0.775	<0.001	0.001	<0.001	<0.0001	<0.001	0.007	0.039	0.065	0.002

Table 2. Comparisons between mean CFD values for more obstructed side and less obstructed side. MOS = More Obstructed Side; LOS = Less Obstructed Side. P2, P4 and P5 and WSS1 showed no statistical difference between MOS and LOS. **Bold** = statistically significant differences.

FIGURE LEGENDS

Figure 1. Example of CT scan in axial and coronal view showing where CFD data were calculated on the More Obstructed Side. $P_1 = 0 \text{ Pa}$ and $T_1 = 19^\circ\text{C}$ for every patient.

Figure 2. Figure 2 shows a patient with a severe obstruction in the right nasal fossa according to a) Total Pressure (Pa), b) Heat Flux (W/m^2), c) Wall Shear Stress (Pa), and d) Streamlines. Streamlines are colored 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.

Figure 3. shows the same patient as in Figure 2 in section planes according to a) Temperatures ($^\circ\text{C}$) and b) Velocities (m/s). Temperatures were lower in the LOS. However, Velocities were higher on the LOS when NAO was total.

Figure 4. shows the changes in Total Pressure and Heat Fluxes. A huge Pressure and Heat Flux drop was found after the septal deviation.

Video 1. shows streamlines and airflow according to MOS and LOS. Streamlines are colored according to Total Pressure. We observed very different air paths between the two sides.

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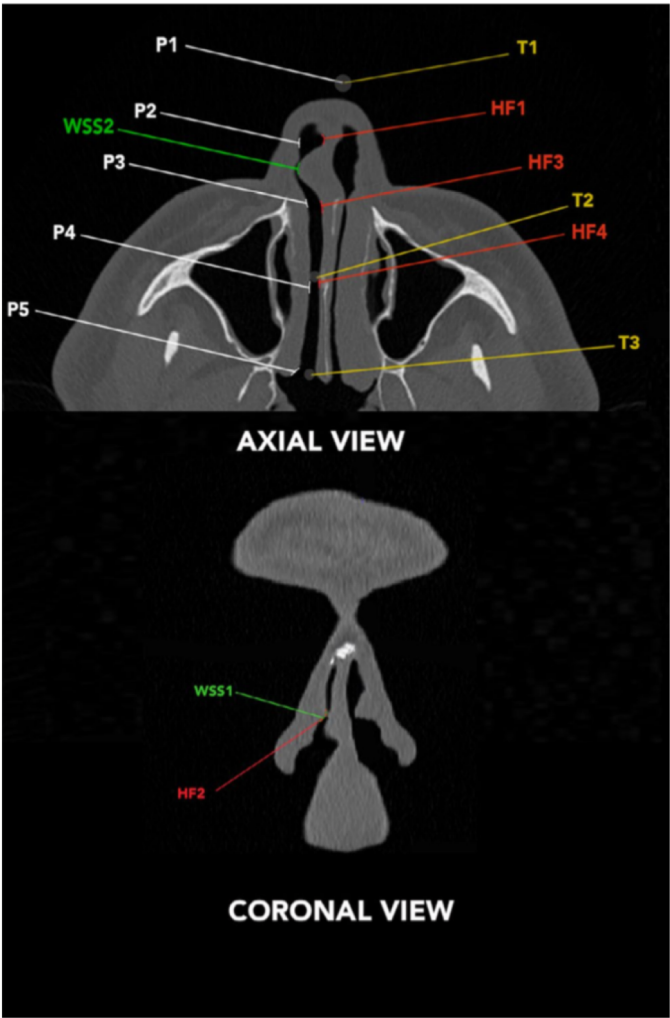


Figure 01

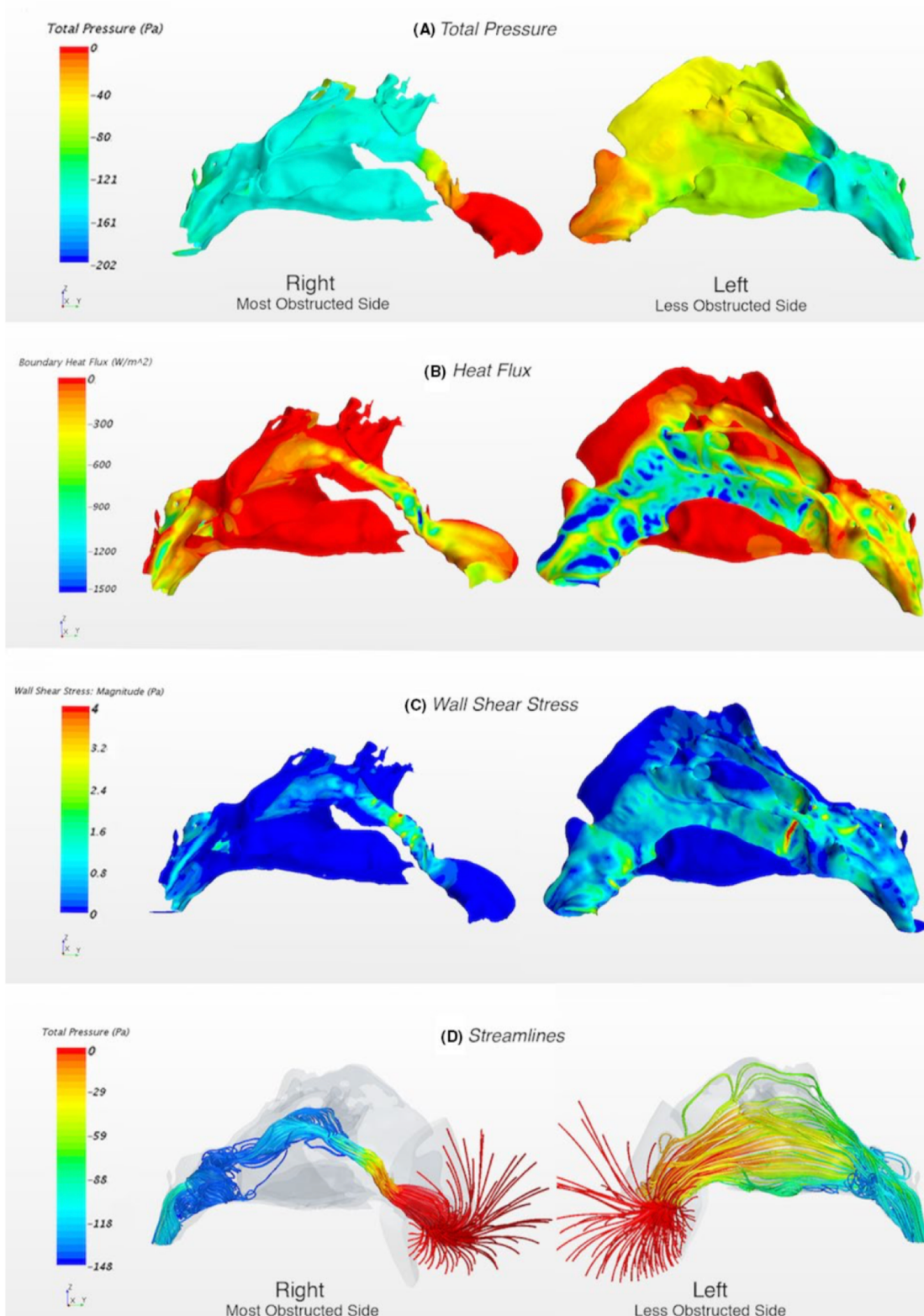


Figure 02

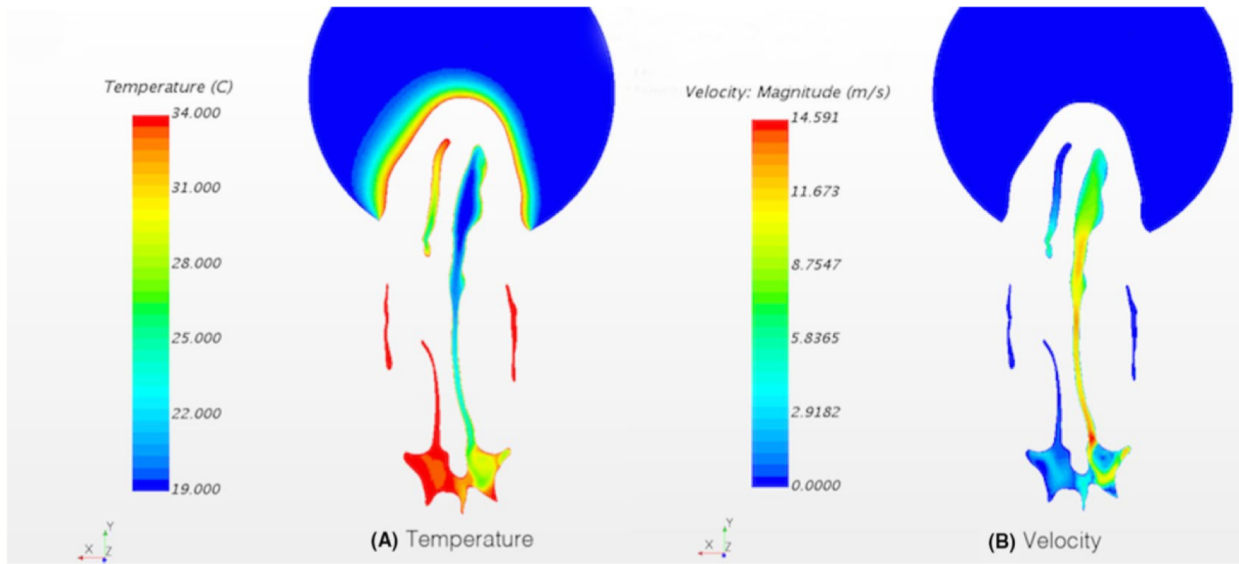


Figure 03

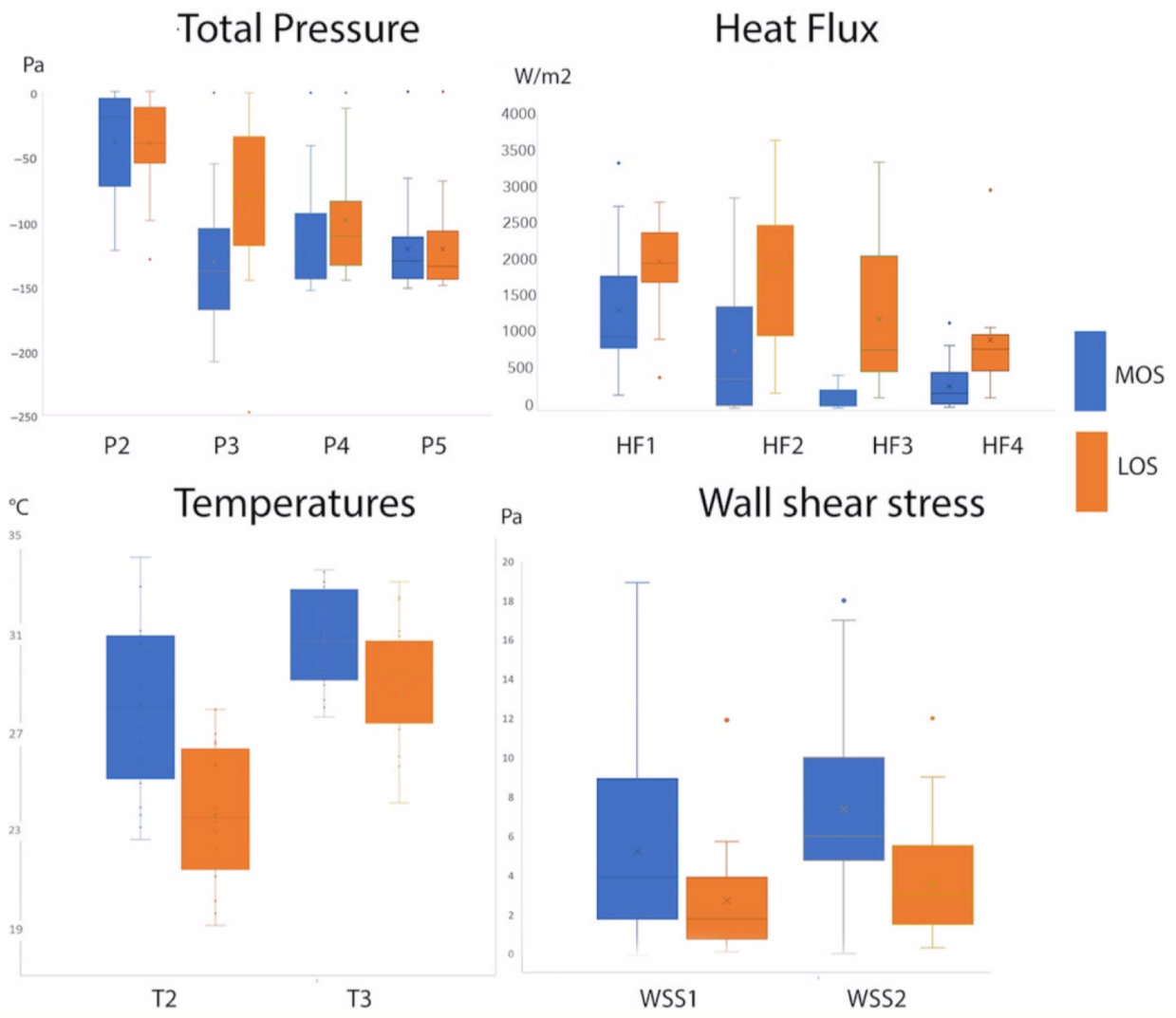


Figure 04