

Rhinomanometry Versus Computational Fluid Dynamics: Correlated, But Different Techniques

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SUPPLEMENTAL MATERIAL

MATERIALS AND METHODS

Cohort Demographics

The inclusion criteria were age ≥ 18 years and NAO symptoms associated with structural abnormalities (septal deviation, hypertrophied inferior turbinate, or nasal valve stenosis). Patients with septal perforation, cleft palate, nasal tumor, ongoing respiratory infection, complete nasal obstruction after vasoconstriction (i.e., nasal resistance is infinite), or current use of monoamine oxidase inhibitors (contraindication of vasoconstrictor drugs) were excluded. The pre-surgery CT scan was indicated to investigate symptoms not elucidated by routine clinical exams, such as headache and postnasal drip sensation. All patients had failed clinical management and were on the waiting list for NAO surgery.

Vasoconstriction and timeline of data acquisition

Topical vasoconstriction was employed to abolish fluctuations in mucosal engorgement that could confound the comparison between rhinomanometry and CFD. Rhinomanometry was performed both before and after vasoconstriction to quantify the effect of mucosal decongestion on nasal resistance. All participants waited at least 20 minutes in a resting room before the study started. After completing the pre-vasoconstriction rhinomanometry measurements, a topical vasoconstrictor was applied (oxymetazoline 0.05%, two sprays of 0.1ml in each nostril followed by an extra spray 5 minutes later). The CT scans were acquired 78 ± 17 minutes after vasoconstriction using a CT protocol previously described.²⁷ The post-vasoconstriction rhinomanometry measurements were performed 30 ± 14 minutes after CT acquisition. Previous studies suggest that mucosal decongestion persists for at least 4 hours after vasoconstriction,²⁶ thus it was assumed that the state of mucosal engorgement was the same in the CT scans and in the post-vasoconstriction rhinomanometric measurements.

Reconstruction of Nasal Geometry

The CT scans had pixel sizes ranging from 0.29 to 0.35 mm, slice thickness from 0.5 to 1.3 mm, and slice increment from 0.3 to 0.6 mm. The nasal airspace was segmented from nostrils to nasopharynx using a range of -1024 to -550 HU in MimicsTM (Materialise, Leuven, Belgium). The lower limit of this range (-1024 HU) represents the radiodensity of air, while the upper limit (-550 HU) is the midpoint of a wide range of possible segmentation thresholds (-800 to -300 HU). The value of -550 HU was selected because it minimized the artefacts in the 3D reconstruction, thus minimizing the amount of manual editing required to segment the airspace.²⁷ The paranasal sinuses were excluded manually because they are expected to have a negligible contribution to nasal resistance, while their inclusion would increase the computational cost.

Rhinomanometry

Active anterior rhinomanometry (Rhinomanometer NR6, GM Instruments, Kilwinning, UK) was performed as recommended by the Standardisation Committee on Objective Assessment of the Nasal Airway.²⁹ Unilateral nasal resistance was defined as the mean of three consecutive measurements, each measurement consisting of four breathing cycles. Before each measurement, the face mask was removed and the tape sealing the contralateral nostril was

inspected. Reproducibility of rhinomanometric measurements was quantified with the coefficient of variability (C_v)

$$C_v = \sigma/\mu$$

where σ and μ are respectively the standard deviation and mean of the three consecutive measurements. All RMN measurements were performed by the same operator.

In Vitro Experiments

Plastic replicas of the nasal cavities from six subjects (five NAO patients plus a healthy subject from a previous study³¹) were 3D printed with a resolution of 0.10x0.25x0.25 mm in the SLA iPro-8000 3D printer using the Accura 25 material (**Figure 1A-D**). The nasal replicas were used in *in vitro* experiments to measure the pressure-flow curve. To reproduce the protocol for rhinomanometry, one nostril was occluded with tape (Microfoam 3M). Air pressure was measured with a pressure catheter (Millar Mikro-Cath, Millar, Inc., Houston, TX, USA) pierced through the tape (**Figure 1E**). Since this nostril was occluded with tape, the pressure reading reflected the pressure drop across the nasal cavity (i.e., gauge pressure at the choana). Steady flow through the contralateral nasal cavity was generated by connecting house vacuum to the model outlet using a plastic hose. The flowrate was measured using a flowmeter (Model 4045, TSI Inc., Shoreview, MN, USA) in series with the plastic hose (**Figure 1E**). Pressure was measured for steady flowrates from 0 to 70 L/min in steps of 10 L/min.

Computational Fluid Dynamics Simulations

Tetrahedral meshes were created in ICEM-CFDTM (ANSYS, Canonsburg, PA, USA). All elements had an aspect ratio above 0.3 to avoid distorted elements. A mesh density test revealed that the pressure-flow curve was sensitive to mesh size. For a pressure drop of 200 Pa from nostrils to outlet in one model, bilateral airflow decreased from 1085 to 1044, 1006, 989, and 982 ml/s when mesh size was increased from 1 to 2, 4, 8, and 17 million elements. Given the large sample size in this study, a mesh size of 4 million tetrahedral elements was selected as a good balance between accuracy and computational cost. Mesh sizes of approximately 4 million elements have been used in several prior studies.

To reproduce the experimental setup, one nostril was set as a wall (zero flow), while air flowed freely through the contralateral nostril (**Figure 2B**). The no-slip boundary condition (i.e.,

zero velocity) was applied at all walls. Atmospheric pressure was applied at a spherical surface located in front of the face (**Figure 2D**). An outlet pressure boundary condition was applied with a constant, negative pressure at the outlet to generate inspiratory flow. Separate simulations were performed to obtain the pressure-flow curves of the left and right cavities. The inlet boundary conditions for the $k\omega$ model were 5% turbulence intensity and a turbulent length scale of 1mm.

The outlet pressure required to generate a gauge pressure of -75 Pa at the choana was estimated by performing preliminary CFD simulations to quantify the relationship between outlet pressure (P_{outlet}) and choana pressure (P_{choana}) in each model. Data from these preliminary simulations were fitted with the power law $P_{\text{outlet}} = a * |P_{\text{choana}}|^b$, where a and b are fitted constants, so that the outlet pressure corresponding to $P_{\text{choana}} = -75$ Pa could be computed. A power law fit was also used to quantify nasal resistance for the comparison between *in vitro* experiments and CFD simulations. In this case, the pressure-flow curve was fitted with the power law $Q = c * |P_{\text{choana}}|^d$, so that nasal resistance could be computed as $R = |P_{\text{choana}}| / Q = |P_{\text{choana}}|^{1-d} / c$, where c and d are fitted constants.

Data Analysis

For each patient, the most obstructed cavity was defined as the cavity with higher visual analog scale (VAS) score before mucosal decongestion. The least obstructed cavity was defined as the cavity with lower VAS score before mucosal decongestion.

Statistical Analysis

Statistical analysis performed for the left cavity only ($n=25$ patients) or right cavity only ($n=25$ patients) provided nearly the exact same results as for the combined sample of 50 unilateral measurements.³⁶ Therefore, for clarity of presentation, only the statistical analysis for the combined sample of 50 unilateral values is presented for the correlation between CFD and RMN.

RESULTS

Correlation between subjective and objective measures of nasal airflow

No correlation was found between subjective and objective measures of nasal airflow when the datasets before mucosal decongestion and after mucosal decongestion were investigated independently (**Table S1**). When the two datasets were combined, a weak correlation was found between unilateral airflow measured with rhinomanometry and the VAS score in the most obstructed cavity ($r = -0.42$, $p = 0.003$) (**Table S2**).

Correlation between different subjective measures of nasal patency

The NOSE score had a weak correlation with the bilateral and unilateral VAS scores before mucosal decongestion (**Table S3**). However, the NOSE score was not correlated with the bilateral and unilateral VAS scores after mucosal decongestion (**Table S3**).

Table S1 – Pearson correlation between subjective and objective measures of nasal airflow in a cohort of 25 patients with nasal airway obstruction. Datasets collected before and after mucosal decongestion were analysed separately.

BILATERAL MEASUREMENTS				
TECHNIQUE	VARIABLE	NOSE	VAS before decongestion	VAS after decongestion
RMN	Resistance	N.S.	N.S.	N.S.
	Flowrate	N.S.	N.S.	N.S.
CFD	Resistance	N/A	N/A	N.S.
	Flowrate	N/A	N/A	N.S.
UNILATERAL MEASUREMENTS – MOST OBSTRUCTED CAVITY				
TECHNIQUE	VARIABLE	NOSE	VAS before decongestion	VAS after decongestion
RMN	Resistance	N.S.	N.S.	N.S.
	Flowrate	N.S.	N.S.	N.S.
CFD	Resistance	N/A	N/A	N.S.
	Flowrate	N/A	N/A	N.S.
UNILATERAL MEASUREMENTS – LEAST OBSTRUCTED CAVITY				
TECHNIQUE	VARIABLE	NOSE	VAS before decongestion	VAS after decongestion
RMN	Resistance	N.S.	N.S.	N.S.
	Flowrate	N.S.	N.S.	N.S.
CFD	Resistance	N/A	N/A	N.S.
	Flowrate	N/A	N/A	N.S.

Abbreviations: RMN = rhinomanometry; CFD = computational fluid dynamics; NOSE = Nasal Obstruction Symptom Evaluation;^{24,25} VAS = visual analog score (0 = no obstruction, 10 = complete obstruction); N.S. = not statistically significant; N/A = not applicable (CFD data are not available before mucosal decongestion).

Table S2 – Pearson correlation between the visual analog score (VAS) of nasal airflow sensation (0 = no obstruction, 10 = complete obstruction) and rhinomanometry measurements in a cohort of 25 patients with nasal airway obstruction. Measurements collected before and after mucosal decongestion were combined into a single dataset.

BILATERAL MEASUREMENTS		
VARIABLE	r	P-value
Resistance	N.S.	N.S.
Flowrate	N.S.	N.S.
MOST OBSTRUCTED CAVITY		
VARIABLE	r	P-value
Resistance	N.S.	N.S.
Flowrate	-0.42	0.003
LEAST OBSTRUCTED CAVITY		
VARIABLE	r	P-value
Resistance	N.S.	N.S.
Flowrate	N.S.	N.S.

Abbreviations: r = correlation coefficient; N.S. = not statistically significant.

Table S3 – Correlation between the NOSE and VAS scores. The NOSE score is a measure of bilateral airflow in the one-month period preceding the survey. The VAS score is an instantaneous measure of nasal airflow and it can be either bilateral or unilateral.

	BILATERAL		MOST OBSTRUCTED CAVITY		LEAST OBSTRUCTED CAVITY	
	r	P-value	r	P-value	r	P-value
BEFORE DECONGESTION	0.50	0.013	0.42	0.040	0.50	0.012
AFTER DECONGESTION	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

Abbreviations: r = correlation coefficient; N.S. = not statistically significant.