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ORIGINAL RESEARCH

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Objective diagnosis of internal nasal valve collapse by four-phase rhinomanometry

Pierre Gagnieur MD[1] | Maxime Fieux MD[2,3,4,5] | Bruno Louis MD[4,5] | Emilie Béquignon MD[4,5,6] | Sophie Bartier MD[4,5,7] | Delphine Vertu-Ciolino MD[3,7,8,9]

[1]Service de chirurgie maxillo-faciale et plastique de la face, Centre Hospitalier Lyon Sud, Hospices Civils de Lyon, Pierre Bénite cedex, France

[2]Service d'ORL, d'otoneurochirurgie et de chirurgie cervico-faciale, Centre Hospitalier Lyon Sud, Hospices Civils de Lyon, Pierre Bénite cedex, France

[3]Université Lyon 1, Université de Lyon, Lyon, France

[4]INSERM, IMRB, Université Paris Est Créteil, Créteil, France

[5]CNRS EMR 7000, Créteil, France

[6]Service d'ORL et de chirurgie cervico-faciale, Centre Hospitalier Intercommunal de Créteil, Créteil, France

[7]Service d'ORL et de chirurgie cervico-faciale, AP-HP, Centre Hospitalier Universitaire Henri Mondor, Créteil, France

[8]Hospices Civils de Lyon, hôpital Edouard Herriot, Service d'ORL et de chirurgie cervico-faciale, Lyon, France

[9]CNRS UMR 5305, LBTI, Lyon, France

Correspondence
Maxime Fieux, Service d'ORL, d'otoneurochirurgie et de chirurgie cervico-faciale, Hospices Civils Lyon, Centre Hospitalier Lyon Sud, 165 Chemin du Grand Revoyet, 69310 Pierre-Bénite, France.
Email: maxime.fieux@chu-lyon.fr

Abstract

Background: Internal valve collapse is a frequent cause of nasal obstruction but remains poorly understood and is sometimes treated inappropriately as a result. No functional or imaging test for the condition has been validated and the reference diagnostic technique is physical examination. The objective of this study was to evaluate the potential of four-phase rhinomanometry as a diagnostic test for internal valve collapse.

Methods: In a case–control diagnostic accuracy study, the nostrils of adult patients consulting for chronic nasal obstruction were classified as "collapsed" or "non-collapsed" based on clinical findings. Four-phase rhinomanometry was performed in all patients. The area defined by the path of the flow/pressure curve in the two phases of inspiration (the "inspiratory loop area" or "hysteresis loop area") was calculated for both nasal cavities and the threshold value with the highest Youden index was identified.

Results: Sixty-six patients (132 nostrils) were included with 72 nostrils classified as collapsed and 60 as non-collapsed. Before nasal decongestion, the inspiratory loop area with the highest Youden index was 17.3 Pa L s^{-1} and the corresponding sensitivity and specificity were 88.3% (95% confidence interval, 80.0–95.0%) and 89.9% (82.6–95.7%), respectively.

Conclusions: In these patients, a cutoff inspiratory loop area in four-phase rhinomanometry data reproduced clinical diagnoses of internal valve collapse with high sensitivity and specificity. This method may offer a firmer basis for treatment indications than subjective physical examinations.

Level of evidence: Level 4.

KEYWORDS
diagnosis, nasal obstruction, rhinomanometry

1 | INTRODUCTION

Chronic nasal obstruction is the fourth most common reason for ENT consultations in France.[1] Its prevalence is hard to estimate but the condition may affect up to 30% of the population.[2] Nasal obstruction is defined as insufficient nasal airflow resulting in respiratory discomfort and is considered chronic when symptoms persist for more than 3 months.[1] The main etiologies are constitutional or acquired deformities of the various cartilages or nasal bones.[3,4] Collapse of the internal valve (internal valve collapse) is a rarer cause of nasal obstruction and is more rarely considered by nasal surgeons.[5] Missing this diagnosis can have serious consequences however: long-term nasal corticosteroid treatment may be incorrectly initiated, and septoplasty or turbinoplasty surgery may be offered to patients but prove ineffective or even deleterious.[3,6]

The internal valve region is the flow-limiting segment of the nasal cavity.[7] It is bounded by the septum, the caudal edge of the upper lateral cartilage, and the cephalic edge of the lower lateral cartilage. On entering this constricted segment, the airflow accelerates because of the Venturi effect and the intraluminal pressure drops in accordance with Bernoulli's principle.[8] Depending on the rigidity of the structures,[9] this pressure drop can lead to the collapse of the internal valve, obstructing the nasal passage.[10] Internal valve collapse can be caused by trauma, aging, paralysis, but commonly occurs as an adverse effect of rhinoplasty surgery.[11]

No imaging or functional test has ever been validated and diagnosis rests on clinical findings[10]: collapse of the upper lateral cartilages on moderate inspiration and/or breathing facilitated by the modified Cottle maneuver (supporting the upper lateral cartilages using a cotton swab).[12] The development of rhinomanometry has significantly improved the diagnosis of chronic nasal obstruction,[13] by limiting the reliance on subjective clinical examinations. For internal valve collapse, while the diagnostic performance of the FRIED test, based on posterior rhinomanometry, is reportedly limited (a sensitivity of 82% and specificity of 59%),[14] four-phase rhinomanometry, which correlates better with patients' sensations,[15] should reveal a hysteresis loop in the inspiratory curve in patients with internal valve collapse.[16] However, this notion of a looped curve has not been precisely defined and to our knowledge, no data have been published on the use of four-phase rhinomanometry to diagnose internal valve collapse. The objective of this work was therefore to evaluate the potential of four-phase rhinomanometry as a diagnostic test for internal valve collapse.

2 | METHODS

2.1 | Study design and population

This was a case–control diagnostic accuracy study of all adult patients (> 18 years old) who attended the otolaryngology clinic of Lyon University Hospital for chronic nasal obstruction between January 2019 and January 2021. Patients were excluded if the obstruction was due to a tumor, chronic sinusitis or sinonasal polyposis, as determined by endoscopic examination and/or imaging.

2.2 | Ethics

The study was conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee (approval no. 21-137) but written consent was waived (retrospective study). All data were anonymized.

2.3 | Data collection and clinical evaluation

The data collected were the patients' age, sex, body mass index (BMI), atopic status, smoking status, cardiovascular history (to eliminate a contraindication for oxymetazoline), and history of nasal trauma, paralysis or rhino-sinus surgery. Each patient was examined by two senior ENT physicians in a blinded fashion in daily clinical routine. During the first consultation, patients were examined and rhinomanometry was scheduled. Patients were then reexamined by the second physician when they returned for the rhinomanometry measurements. Disagreements in the results of the physical examinations were resolved at the last medical visit by a third senior ENT physician.

The physical examination involved: (i) static examination of the nasal pyramid: nasal shape, presence of deviation, frontal width of the middle third (thin, normal, wide), appearance of the dorsum on profile view (straight, hump, kyphosis), presence of anterior septal dislocation and/or inferior turbinate hypertrophy on anterior rhinoscopy, presence and type of septum deviation on nasal endoscopy (anterior dislocation, caudal dislocation, C-shaped deviation, or various combinations thereof); and (ii) functional examination: behavior of the lateral cartilage on weak or moderate inspiration, effect of passive abduction of the triangular cartilages with a cotton swab (modified Cottle maneuver), and effect of lateral traction of the nostril and cheek (Cottle maneuver). Internal valve collapse was defined by the observation of lateral wall collapse on low to moderate inspiration and/or a reduced sense of obstruction during the modified Cottle maneuver. Patients who had lateral wall collapse on inspiration but whose breathing was not improved by the modified Cottle maneuver were not considered to have internal valve collapse.

2.4 | Four-phase rhinomanometry

The four-phase anterior rhinomanometry measurements were performed by a third ENT physician blinded to the patients' diagnosis ("collapsed" or "non-collapsed") using a Rhinolab 4-Rhino device (Rhinolab GmbH, Freiburg, Germany), and the 4-Rhino software (v. 6.1.1). All patients were examined in sitting position after 30 min rest. The contralateral nostril was occluded with medical tape, to avoid modifying the structure of the nasal wing and nasal valve area. The data collected for each nasal cavity were the vertex resistance (VR), the effective resistance (REff) and the flow/pressure curve.[7] The area of the hysteresis loop in the flow/pressure curve, the "inspiratory loop area" was obtained (Figure 1) by subtracting the area under the curve during phase 2 of inspiration from the area under the curve during phase 1. A nasal decongestant was then administered (oxymetazoline spray, 50 μg in each nostril if not contraindicated) and measurements were repeated under identical conditions 15 min later.[17]

2.5 | Statistical analysis

Univariate comparisons between collapsed and non-collapsed patients were performed using *t* tests for quantitative variables (Mann–

Whitney tests if the assumptions of the *t* test were not met) and chi square tests for categorical variables (Fisher exact tests for small sample sizes). To evaluate the diagnostic accuracy of the inspiratory loop area for internal valve collapse (independent of prevalence, the intrinsic diagnostic accuracy), the values obtained for the right and left nasal cavity were separately compared before and after nasal decongestion with the clinical diagnosis of each patient (collapsed or non-collapsed), used here as the reference test. Contingency tables were built by dichotomizing the loop areas at different thresholds. The corresponding receiver operating characteristic (ROC) curve was plotted and the threshold with the highest Youden index (combined sensitivity and specificity) was selected.[18] After confirming that the results obtained for left and right nostrils were equivalent, the data were combined to increase the size of the dataset and thus the power of the statistical analyses. ROC curves were also constructed for the effective resistance and vertex resistance as well as for the FRIED test applied to the same data. The threshold for statistical significance was set at .05. All analyses were performed with the software R (v. 4.1.2, www.r-project.org).

3 | RESULTS

3.1 | Study population

Sixty-six patients with chronic nasal obstruction were included, 36 of which were diagnosed as having internal valve collapse (26 bilaterally, 10 unilaterally), while the remaining 30 were classified as non-collapsed. Patient characteristics are reported in Table 1 and physical examination results in Table 2. There were no significant differences

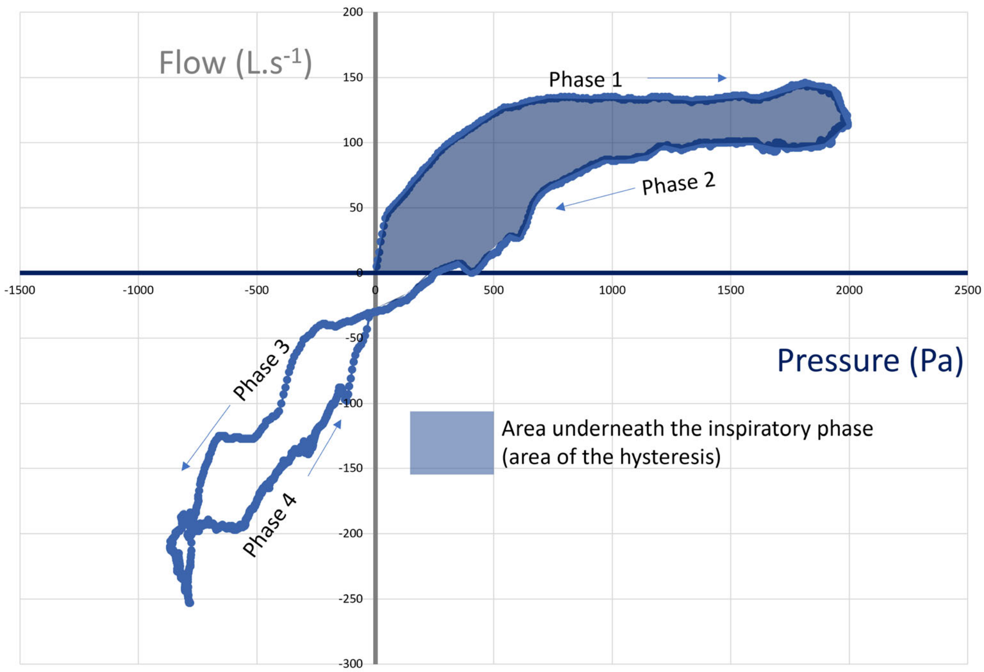

FIGURE 1 Four-phase rhinomanometry flow/pressure curve. The area of the hysteresis loop in the flow/pressure curve, the "inspiratory loop area" was obtained by subtracting the area under the curve during phase 2 of inspiration from the area under the curve during phase 1 and is shown in blue. Abbreviations: Pa, Pascal; L s^{-1}, liter per second

TABLE 1 Study population

	Collapsed (n = 36)	Non-collapsed (n = 30)	*p* value
Age (years)	40 (±15)	29 (±11)	.001*
Female Gender	14 (39%)	12 (40%)	1
Height (cm)	175 (±9)	174 (±10)	.27
Weight (kg)	75 (±14)	75 (±18)	.93
Tobacco use	31 (86%)	23 (77%)	.50
Atopy	32 (89%)	23 (77%)	.32
History of nasal trauma	24 (67%)	17 (57%)	.56
History of rhino-sinus surgery	2 (6%)	1 (3%)	1

Note: The values correspond to the numbers (proportions) for the categorical variables and the means (standard deviation) for the quantitative variables.
*Statistical significance ($p < .05$).

TABLE 2 Nasal clinical evaluation

	Collapsed ($n = 36$)	Non-collapsed ($n = 30$)	*p* value
Nasal ethnic type			
Caucasian	36 (100%)	30 (100%)	.46
African	0 (0%)	0 (0%)	
Asian	0 (0%)	0 (0%)	
Deviated nose	17 (47%)	19 (63%)	.29
Kyphosis	16 (44%)	17 (46%)	.46
Width of the middle third			
Narrow	16 (44%)	3 (10%)	.03*
Normal	19 (53%)	23 (77%)	
Wide	1 (3%)	4 (13%)	
Septal deviation	26 (87%)	32 (89%)	1
Anterior dislocation	6 (17%)	13 (43%)	.05*
Inferior dislocation	11 (31%)	18 (60%)	.01*
C-shaped	23 (64%)	15 (50%)	.32
Vomerian spur	21 (58%)	17 (57%)	.58
Turbinate hypertrophy	6 (16%)	15 (50%)	.005*
Upper lateral cartilage collapse	36 (100%)	0 (0%)	.001*
Modified Cottle maneuver	36 (100%)	0 (0%)	.001*
Cottle maneuver	10 (28%)	2 (6%)	.003*

Note: The values correspond to the numbers (proportions) for the categorical variables and the means (standard deviation) for the quantitative variables.
*Statistical significance ($p < .05$).

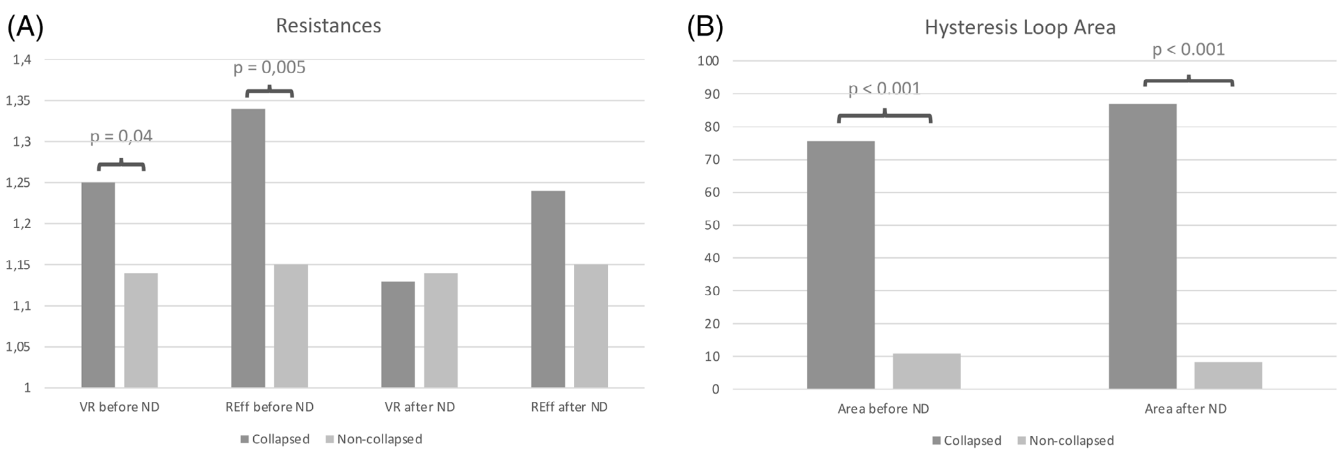

FIGURE 2 Four-phase rhinomanometry resistances (A) and hysteresis loop area (B) before and after nasal decongestion. Histograms of the effective resistance (REff) and vertex resistance (VR) before and after nasal decongestion (ND) and inspiratory loop area before and after ND. Two groups of nostrils are detailed, collapsed in dark gray and non-collapsed in light gray. *p* value of statistical significance are shown in both (A) and (B). Abbreviations: ND, nasal decongestion; REff, effective resistance; VR, vertex resistance

between the two groups in terms of history of nasal trauma and nasal surgery, age, sex, height, weight, smoking habit or atopic status. In terms of physical examination results, the middle third of the nose was significantly thinner in the collapsed group (16/36, 44%) than in the non-collapsed group (3/30, 10%; $p = .03$) and there was more turbinate hypertrophy in the non-collapsed group (15/30, 50%) than in the collapsed group (6/36, 17%; $p = .005$).

3.2 | Four-phase rhinomanometry

Effective resistance and vertex resistance, and inspiratory loop area before nasal decongestion all differed significantly between the two groups (Figure 2A,B). After nasal decongestion on the other hand, the only significant difference between the two groups was for the loop area, which was larger in the collapsed group than in the non-

TABLE 3 Four-phases rhinomanometry results (data by nostril)

	Collapsed (n = 60)	Non-collapsed (n = 72)	*p* value
VR before ND (Pa L s^{-1})	2.41 (±2.76)	1.95 (±1.91)	.037*
REff before ND (Pa L s^{-1})	3.47 (±4.10)	2.14 (±2.36)	.005*
VR after ND (Pa L s^{-1})	2.14 (±2.64)	1.67 (±1.14)	.88
REff after ND (Pa L s^{-1})	2.51 (±3.10)	2.51 (±3.65)	.21
VR-REff before ND (Pa L s^{-1})	−1.07 (±2.60)	−0.21 (±1.10)	.001*
VR-REff after ND (Pa L s^{-1})	−0.80 (±3.05)	−0.35 (±2.26)	.016*
Area before ND (Pa L s^{-1})	67.5 (±81.8)	7.9 (±17.6)	<.001*
Area after ND (Pa L s^{-1})	60.3 (±122.5)	7.1 (±9.6)	<.001*

Note: Values are means (standard deviation) for quantitative variables.
Abbreviations: ND: nasal decongestion (with oxymetazoline); REff, effective resistance; VR, vertex resistance; VR-REff, difference between VR and REff.
*Statistical significance ($p < .05$).

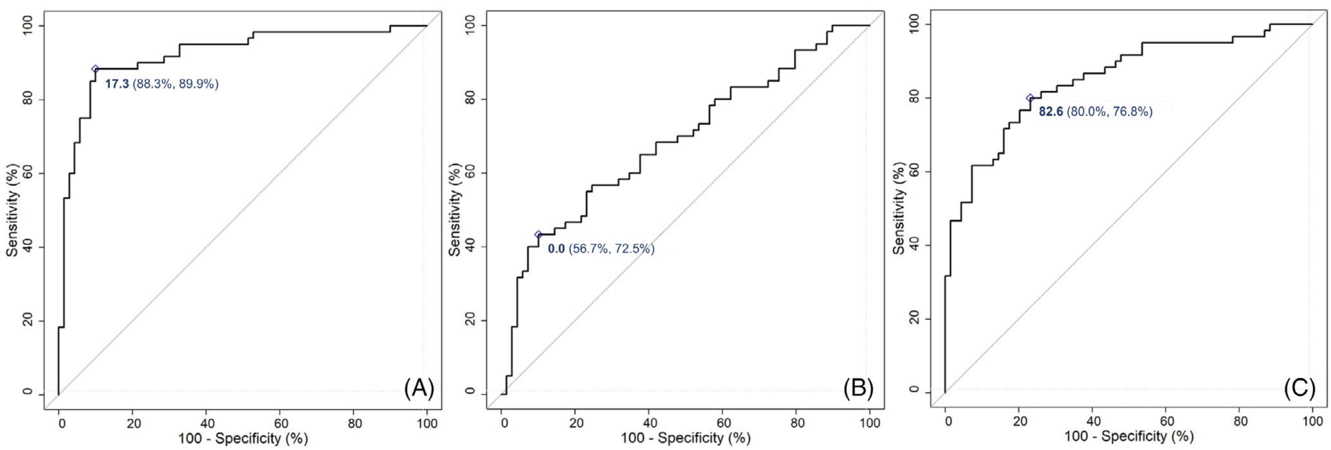

FIGURE 3 ROC curves constructed from the hysteresis loop area (A), difference in resistances (B) and FRIED test (C). The ROC curve constructed from the hysteresis loop area (A), from the difference in resistances (VR − REff) (B) and form the FRIED test results (C) are given with the highest Youden index in Pa L s^{-1}, a corresponding sensitivity and specificity respectively in %

collapsed group (mean ± standard deviation, 87.0 ± 104.9 vs. 8.2 ± 8.8 Pa L s^{-1}; *p* <.001). Rhinomanometry results are presented in full in Table 3.

3.3 | ROC curves

The data for right and left nostrils were analyzed together, as explained in the methods section. The threshold value of the inspiratory loop area (hysteresis area) before nasal decongestion with the highest Youden index was 17.3 Pa L s^{-1}, with a corresponding sensitivity and specificity of 88.3% (95% confidence interval, 80.0–95.0%) and 89.9% (82.6–95.7%), respectively (Figure 3A). In the data obtained after nasal decongestion, the optimal threshold was 15.1 Pa L s^{-1} and the corresponding sensitivity and specificity were 91.8% (83.7–98.0%) and 87.3% (78.2–94.5%), respectively. The ROC curve constructed from the difference in resistances (VR − REff) indicated an optimal threshold of 0, for which the sensitivity and specificity were 56.7% (45.0–70.0%) and 72.5% (62.3–82.6%), respectively (Figure 3B). The ROC curve constructed from the FRIED test results revealed an optimal threshold of 82.6 mL s^{-1}, with a corresponding sensitivity and specificity of 80.0% (70.0–90.0%) and 76.8% (66.7–87.0%), respectively (Figure 3C).

4 | DISCUSSION

In this group of patients, the inspiratory loop area in four-phase rhinomanometry curves was significantly larger in patients with internal valve collapse than in those with a different cause of nasal obstruction. A cutoff inspiratory hysteresis area accurately reproduced the results of physical examination as the reference standard. These results suggest that four-phase rhinomanometry can be used in this way to diagnose internal valve collapse with a high sensitivity and specificity (up to 90%).

During the first phase of inspiration, the intranasal pressure decreases on lowering of the diaphragm) and the airflow increases accordingly. Internal valve collapse can occur at a certain flow rate because of the Venturi effect, leading to a drop in the flow rate at the same differential pressure. This leads to hysteresis in the flow/pressure curve in the second phase of inspiration, when the differential pressure decreases once more. This phenomenon has never previously been studied or quantified as a means of discriminating patients with internal valve collapse from those with other causes of nasal obstruction. The results of this study show that hysteresis can also be observed, albeit to a lesser extent, in patients without internal valve collapse, with a mean loop area of 11.0 Pa L s^{-1} (±15.9) in the non-collapsed group. This can be explained by the inertia of the nasal walls, which are not perfectly elastic, and reflects the dynamic narrowing of the internal nasal valve area during inspiration, which in these patients has no clinical impact. The optimal threshold value of the inspiratory loop area to diagnose or eliminate internal valve collapse in this group of patients was 17.3 Pa L s^{-1}. We chose to use the measurements before nasal decongestion (with oxymetazoline) because we believe these more reliably reflect patients' respiratory physiology. Nasal decongestion is useful to diagnose nasal hyperreactivity[16] but does not reflect the pathophysiology of internal valve collapse. The mean inspiratory loop areas were similar before and after nasal decongestion in both groups (75.5 Pa L s^{-1} vs. 87.0 Pa L s^{-1} in the collapsed group and 11.0 Pa L s^{-1} vs. 8.2 Pa L s^{-1} in the non-collapsed group, respectively). This suggests that the potential decrease in resistance (and thus increase in flow) induced by vasoconstrictors has little or no effect on valve collapse. This may be because vasoconstrictors affect the entire nasal mucosa, increasing the diameter at the entrance and exit of the valve by a similar amount. Since the Venturi effect, which depends on the difference in inlet/outlet diameter, is not strengthened[19] nasal decongestion has no aggravating effect on internal valve collapse. Another possible explanation for this small effect of vasoconstriction is the low vascular density of the valve area.

The optimal diagnostic accuracy with the inspiratory loop area (sensitivity, 88.3%; specificity, 89.9%) was much higher than obtained from the difference between VR and REff (sensitivity, 56.7%, specificity, 72.5%), a measure described by Vogt et al.,[7] and higher also than obtained with the FRIED test based on posterior rhinomanometry, both as measured here (sensitivity, 80.0%, specificity, 76.8%) and as reported by Maalouf et al. (sensitivity, 82%, specificity, 59%).[14] The lower diagnostic accuracy of the FRIED-test is probably due to the greater susceptibility of posterior rhinomanometry to measurement bias. In posterior rhinometry indeed, the pressure sensor is placed inside the mouth and measurements are therefore affected by the position of the soft palate.[7,20] In four-phase rhinomanometry on the other hand, the sensor is placed at the entrance of the nasal cavity, a more reproducible and reliable position for measuring the pressure of the nasal cavity with reduced inter-individual variability.

To our knowledge, no functional or imaging test has ever been shown to have such a high level of diagnostic accuracy for internal valve collapse. The reference standard is still physical examination, which is known to be limited by inter-practitioner and inter-patient variability.[14] Our results suggest the inspiratory loop area in four-phase rhinomanometry offers a similar level of specificity and sensitivity as physical examination, while being an objective test. This could have immediate benefits in clinical practice. Indeed, since the treatment options for internal valve collapse vary in difficulty and associated risks[12] (rhinoplasty surgery with autologous cartilage grafting,[21] titanium[22] or bio-absorbable implants,[23,24] injection of fillers,[25,26] insertion of valve dilators), diagnostic objectivity is essential to validate surgical indications. This should improve patient adherence to the proposed treatment, while the presence of an objective measure in patients' medical files should help to resolve medicolegal problems that may arise from adverse outcomes.[27–29]

The studied cohort was representative of the population of patients typically seen in otorhinolaryngology clinics for chronic nasal obstruction. Indeed, both groups of patients had REff values greater that 1 before decongestion (1.34 and 1.15 respectively in the collapsed and non-collapsed groups), corresponding to a high level of nasal obstruction.[7] Our results are therefore relevant to clinical practice. The inspiratory loop area is calculated directly from the flow-pressure curve produced by the four-phase rhinomanometry software and requires no specific training for practitioners, and no additional measurements for patients. The study avoided various biases often associated with diagnostic test accuracy studies.[30–32] Additional strengths were the blinding of the two physical examinations and of the four-phase rhinomanometry measurements with respect to the clinical diagnosis. On the other hand, the limitations of this study include its small size ($n = 66$) and the fact that the four-phase rhinomanometry measurements were performed on each nostril separately, even if the contralateral nostril was occluded with medical tape rather than a nasal plug to avoid altering the structure and biomechanical properties of the studied nostril.[7] Note however that the analysis by nostril rather than by patient increased the statistical power of the analysis and was further justified by the significant proportion of patients (10/36) with unilateral internal valve collapse.

5 | CONCLUSION

The results of this study support the use of the inspiratory loop area in four-phase rhinometry as a reliable and objective alternative to physical examination for the diagnosis of internal valve collapse. Larger studies with a predefined threshold loop area are nevertheless required to confirm these promising results.

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DISCLOSURE

All the authors have read and approved the article's content. No authors have financial or personal conflicts to disclose. Neither the work nor any part of its essential substance, tables or figures have been or will be published or submitted to another scientific journal or are being considered for publication elsewhere.

AUTHOR CONTRIBUTIONS

Pierre Gagnieur, Maxime Fieux, Emilie Béquignon and Delphine Vertu-Ciolino contributed to the conception and design of the study. All authors contributed to the drafting of the article. Maxime Fieux and Bruno Louis performed the statistical analysis.

DATA AVAILABILITY STATEMENT

The datasets used during the current study are available from the corresponding author on reasonable request.

ORCID

Maxime Fieux https://orcid.org/0000-0001-8317-2286
Emilie Béquignon https://orcid.org/0000-0002-5193-5776
Sophie Bartier https://orcid.org/0000-0002-5817-691X

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