Airflow Shape Is Associated With the Pharyngeal Structure Causing OSA

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BACKGROUND: OSA results from the collapse of different pharyngeal structures (soft palate, tongue, lateral walls, and epiglottis). The structure involved in collapse has been shown to impact non-CPAP OSA treatment. Different inspiratory airflow shapes are also observed among patients with OSA. We hypothesized that inspiratory flow shape reflects the underlying pharyngeal structure involved in airway collapse.

METHODS: Subjects with OSA were studied with a pediatric endoscope and simultaneous nasal flow and pharyngeal pressure recordings during natural sleep. The mechanism causing collapse was classified as tongue-related, isolated palatal, lateral walls, or epiglottis. Flow shape was classified according to the degree of negative effort dependence (NED), defined as the percent reduction in inspiratory flow from peak to plateau.

RESULTS: Thirty-one subjects with OSA (mean apnea-hypopnea index score $\pm$ SD, 54 ± 27 events/h) who were 50 ± 9 years of age were studied. NED was associated with the structure causing collapse ($P < .001$). Tongue-related obstruction ($n = 13$) was associated with a small amount of NED (median, 19; interquartile range [IQR], 14%-25%). Moderate NED was found among subjects with isolated palatal collapse (median, 45; IQR, 39%-52%; $n = 8$) and lateral wall collapse (median, 50; IQR, 44%-64%; $n = 8$). The epiglottis was associated with severe NED (median, 89; IQR, 78%-91%) and abrupt discontinuities in inspiratory flow ($n = 9$).

CONCLUSIONS: Inspiratory flow shape is influenced by the pharyngeal structure causing collapse. Flow shape analysis may be used as a noninvasive tool to help determine the pharyngeal structure causing collapse.

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KEY WORDS: flow shape; OSA; site of pharyngeal collapse

ABBREVIATIONS: IQR = interquartile range; NED = negative effort dependence

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OSA is characterized by the narrowing and collapse of pharyngeal structures during sleep. One or more of four key structures may be involved: soft palate, tongue, lateral walls, and/or epiglottis.¹ Determining the pharyngeal structure involved in collapse has been shown to influence structure-specific OSA treatment success.²⁻⁴ Drug-induced sleep endoscopy has been used to detect the site of pharyngeal obstruction and predict the response to oral appliance and hypoglossal nerve stimulation, and to guide the surgical approach for OSA.²⁻⁴ However, drug-induced sleep endoscopy has limitations related to the requirement for sedation and the associated expense. Therefore, an inexpensive, noninvasive technique to determine the structure causing pharyngeal obstruction during natural sleep could improve OSA treatment by allowing more individualized or structure-specific therapy.

Inspiratory flow limitation is a hallmark feature of pharyngeal narrowing. A number of different flow limitation shapes have been recognized in patients with OSA.⁵⁻⁸ A cardinal feature of flow limitation is negative

effort dependence (NED), defined as the reduction from peak to midinspiratory flow with increasing respiratory effort. NED is a reflection of the dynamic compliance of the structure responsible for collapse, with greater NED implying a more compliant airway or structure. We have previously shown that NED varies significantly between patients.^{6,7} It is likely, we think, that the variability in NED results from the interaction between the intrapharyngeal pressure swings and the resulting dynamic behavior of the pharyngeal structure(s) is involved in collapse. We therefore hypothesized that the pharyngeal structure involved in collapse in patients with OSA would dictate the flow limitation shape and NED. Specifically, we postulated that collapse driven by the tongue (larger, stiffer structure) would exhibit minimal NED, whereas collapse at the epiglottis or (isolated) palate (smaller, more compliant structures) would exhibit substantial NED. To test this hypothesis, subjects with OSA were studied with a pediatric endoscope and simultaneous nasal flow and pharyngeal pressure recordings during natural sleep.

Methods

Study Subjects

Men and women 21 to 70 years of age with a previous diagnosis of OSA were recruited from the sleep clinic at Brigham and Women's Hospital. Subjects were excluded if they had significant nasal septal deviation, heart failure, diabetes, or renal insufficiency, or if they were taking sedative medications or muscle relaxants. Written informed consent was obtained before participation in the study, which was approved by the Partners Human Research Committee (Protocol No. 2012-P-000957).

Instrumentation

The instrumentation used in this study has been described previously.⁹ Briefly, in addition to electrodes for sleep staging, a 5-F pressure pharyngeal catheter and a 2.8-mm-diameter pediatric bronchoscope were inserted through the nose after topical application of oxymetazoline 0.05% and lidocaine 4%. The pressure catheter was placed at the level of the epiglottis. Subjects breathed via a nasal mask, which was connected to a pneumotachometer and pressure transducer and a modified CPAP device capable of delivering positive and negative pressures (including 0 cm H₂O). A data acquisition system (Power 1401; Cambridge Electronic Design) was used to capture and synchronize physiologic signals and endoscopic images.

Protocol

Subjects fell asleep in the supine position with the tip of the bronchoscope in the nasopharynx, and CPAP was adjusted to eliminate flow limitation. Once stable nonrapid eye movement sleep was achieved, CPAP was removed for 2- to 3-minute intervals (CPAP drops). After observing the airway at zero pressure for several drops, a small amount of CPAP was added to induce stable flow limitation. CPAP allowed us to hold the airway open such that a particular structure involved in collapse could be carefully observed

throughout the respiratory cycle and correlations between the site of collapse and the flow shape could be made. The bronchoscope was then moved to the oropharynx, and the procedure was repeated. As many sequences of flow limitation as possible were recorded at each level (nasopharynx and oropharynx) throughout the night. In several patients, the influence of the pressure catheter on NED was tested by removing the catheter on expiration during periods of inspiratory flow limitation.

Data Analysis

The structure(s) causing collapse were classified into the following categories: tongue-related obstruction, isolated palatal collapse, pharyngeal lateral wall collapse, and epiglottic collapse. Tongue-related obstruction was defined as narrowing of the airway because of posterior displacement of the tongue both at the velopharynx and oropharynx (Fig 1). Isolated palatal collapse was defined as collapse that occurred at the palate in the absence of tongue-related obstruction, lateral wall collapse, or epiglottic collapse. The lateral walls were considered to be involved if the collapse occurred in the transverse airway dimension on both velopharyngeal and oropharyngeal endoscopic views. Epiglottic obstruction was defined as either anteroposterior or lateral (folding) collapse of the epiglottis. When more than one structure was involved in obstruction, the analysis was performed separately for each structure. The classification was performed by two independent investigators, and discrepancies were resolved by a third investigator.

NED was defined as the percent reduction in inspiratory flow between peak and plateau ($[\text{peak flow} - \text{plateau flow}]/\text{peak flow} \times 100$). Further details regarding NED measurements are described in e-Appendix 1.

Statistics

Continuous variables are reported as mean $\pm$ SD or median (interquartile range [IQR]) as appropriate. Kruskal-Wallis H test compared age, BMI, apnea-hypopnea index, NED, peak and plateau

Figure 1 – A-C, Schematic representation of a posteriorly located tongue. The tongue pushes against the soft palate (A and B) and epiglottis (C), producing bulging of the palate (A and B). The anterior velopharyngeal wall is convex down and results in anteroposterior narrowing, suggesting that the palate is being pushed posteriorly by the tongue (B, velopharyngeal endoscopic view). The tongue base is prominent and obliterates the vallecula (C, oropharyngeal view).

flow, driving pressure, and CPAP levels between pharyngeal structure categories. Post hoc comparisons between groups were performed using Dunn test with Benjamini-Hochberg adjustment. Mallampati scores and sex distribution were compared across categories using the Fisher exact test. Among subjects who presented with collapse at the epiglottis and at a different pharyngeal structure, the Wilcoxon

matched-pairs signed-rank test was used to test the effect of the two structures on NED. NED during the breath immediately before and after catheter removal was compared using a paired *t* test. Receiver operating characteristics analysis was performed to detect the optimal cutoff to differentiate tongue base obstruction and epiglottic collapse from the other structures causing collapse.

Results

Thirty-one patients with OSA (seven women) were studied and had an apnea-hypopnea index score of 56 ± 28 events/h. The subjects were 50 ± 9 years of age and had a BMI of 33 ± 7 kg/m². The characteristics of flow-limited breaths analyzed according to the pattern of pharyngeal collapse ($n = 2,583$) are shown in Table 1. Representative examples of flow patterns and end-expiratory endoscopic views are shown in Figure 2. Despite trying to isolate a single structure using a small amount of CPAP, seven individuals had obstruction at more than one pharyngeal structure (the epiglottis plus either the tongue, the palate, or the lateral walls were involved in pharyngeal collapse in seven patients). In the

remainder of the patients, a single collapsing structure could be identified (either at atmospheric pressure or with a small amount of CPAP), such that correlations between the collapsing structure and a particular flow pattern could be made.

Data were analyzed during atmospheric pressure in 10 patients that showed periods of stable flow limitation on no CPAP. In the remainder of patients ($n = 21$), low levels of CPAP (3.6 ± 2.0 cm H₂O) were used to open the airway at end-expiration and allow movement of a single structure to be clearly visualized. Because CPAP can influence the structure causing collapse, we also tried to identify the site of collapse during atmospheric

TABLE 1] Anthropometric and Flow-Related Characteristics in Each Category of Collapse

Characteristic	Endoscopic Patterns of Collapse			
	Tongue-Related	Isolated Palate	Lateral Walls	Epiglottis
No. of subjects	13	8	8	9
No. of men	9	7	6	9
Age, y	52 ± 8	51 ± 6	45 ± 10	57 ± 8
BMI, kg/m ²	32.5 ± 8.9	31.8 ± 4.2	36.1 ± 4.5	30.8 ± 6.7
AHI, events/h	44.7 ± 28.7	65.2 ± 20.2	63.7 ± 30.8	60.4 ± 23.4
Mallampati score (1/2/3/4)	0/0/0/13	0/0/2/5	0/1/1/4	0/1/1/7
No. of breaths analyzed per patient	59 (21-125)	40 (26-78)	56 (43-122)	25 (13-68)
NED, %	19 (14-25)	45 (39-52) ^a	50 (44-64) ^a	89 (78-91) ^{b,c}
Peak flow, L/s	0.21 ± 0.08	0.27 ± 0.10	0.30 ± 0.13	0.25 ± 0.14
Plateau flow, L/s	0.17 ± 0.07	0.12 ± 0.13	0.13 ± 0.06	0.10 ± 0.12
Peak negative epiglottic pressure at which NED was calculated, cm H ₂ O	-11 (7-13)	-14 (10-18)	-17 (8-22)	...
CPAP at which NED was calculated, cm H ₂ O	2 ± 3	2 ± 1	3 ± 2	3 ± 3

Data are shown as mean ± SD, median (interquartile range), or as otherwise indicated. The total number of subjects in row 1 differs from the total number of subjects enrolled in the study (n = 31) because in seven subjects, two different structures were involved in pharyngeal collapse. Mallampati score was not obtained from three subjects. AHI = apnea-hypopnea index; NED = negative effort dependence.

^aP < .01 (compared with tongue-related).

^bP < .001 (compared with tongue-related).

^cP < .05 (compared with isolated palate).

pressure in these 21 subjects; in three of the 21 individuals, it was too difficult to judge which structure was the primary source of collapse. In the other 18 patients, 16 appeared to have the same mechanism of pharyngeal collapse between atmospheric pressure and during CPAP. In one subject (out of the 18), epiglottic collapse was observed during CPAP but not during atmospheric pressure. Another subject had tongue-related obstruction during CPAP, but isolated palatal collapse during atmospheric pressure.

To determine if the pressure catheter affected the NED measurement, the catheter was removed during expiration 13 times in different patients. No significant difference in NED was seen before and after catheter removal (mean before and after NED difference, 0.3% ± 6.9%; *P* = .88).

Tongue-Related Obstruction

Thirteen patients were judged to have tongue-related obstruction (either at atmospheric pressure or on a small amount of CPAP). In these individuals, there was minimal phasic movement of the tongue and palate with respiration (Videos 1, 2) and a flattened flow limitation pattern, which showed only a small amount of NED (Figs 3A, 3B). Receiver operating characteristics analysis was performed to detect the best cutoff to distinguish tongue-related obstruction from the other structures causing collapse (area under the curve, 0.96; 95% CI, 0.89-1.00). A cutoff ≤ 34.4% had a sensitivity of

100% (95% CI, 72%-100%) and a specificity of 92% (95% CI, 73%-99%) to detect tongue-related obstruction.

Palate

Isolated palatal collapse occurred in eight of 31 patients. These subjects exhibited a moderate amount of NED (median, 45; IQR, 39%-52%), consistent with the large dynamic movement of the palate observed endoscopically. When the palate was the sole or predominant collapsing structure, the velopharynx exhibited phasic collapse and reopening, which we speculate was because of a free-moving palate that was unlikely to be mechanically coupled to the anteriorly located tongue (Fig 3C, Video 3).

Lateral Walls

Lateral wall collapse was the predominant mechanism of pharyngeal obstruction in eight patients, and similar to isolated palatal collapse, was associated with moderate NED (median, 50; IQR, 44%-64%). The high compliance and large dynamic movement of the lateral walls is evident in Figure 3D and Video 4.

Epiglottis

The epiglottis was a cause of pharyngeal obstruction in nine patients, either isolated (n = 2) or in combination with obstruction of other pharyngeal structures (n = 7).

A Posteriorly-located tongue

B Isolated palate

C Lateral walls

Figure 2 – A-C, Thirteen different representative examples of inspiratory flow patterns with corresponding end-expiratory endoscopic views. Single inspiratory flows from each subject are overlaid. The darker tracing represents the ensemble average inspiratory flow. Note that inspiratory flow is more scooped (larger negative effort dependence) among subjects with isolated palatal and lateral wall collapse compared with subjects with posteriorly located tongue. A, Posteriorly located tongue. B, Isolated palate. C, Lateral walls.

Epiglottic collapse was associated with profound NED (median, 89; IQR, 75%-91%). A cutoff $\geq 60.5\%$ differentiated epiglottic collapse from the other structures causing collapse (area under the curve, 0.96; 95% CI, 0.90-1.00), with a sensitivity of 89% (95% CI, 50%-99%) and specificity of 90% (95% CI, 72%-97%). A cardinal feature of epiglottic collapse was its intermittent nature; it would occur for clusters of breaths and then disappear, only to be replaced by another site of collapse.

Such intermittent collapse of the epiglottis occurred in seven out of the nine patients in this group. The other collapsing structure was the tongue ($n = 3$), the palate ($n = 2$), or the lateral walls ($n = 2$). Among these patients with intermittent epiglottic collapse, breaths with epiglottic collapse exhibited markedly greater NED than those breaths without epiglottic collapse ($79\% \pm 6\%$ vs $29\% \pm 8\%$, $P = .0002$) and therefore are subsequently reported separately.

Figure 3 – A-E, Representative examples of flow shape, Epi, and endoscopic images at end-expiration and peak negative inspiratory pressure. A, Tongue-related obstruction (posteriorly located tongue) associated with stable flow limitation (small negative effort dependence [NED]), with little phasic movement from end-expiration to peak negative pressure can be seen at the velopharynx (A) and oropharynx (B) (examples taken from the same subject). C, D, Isolated palate (C) and lateral wall (D) involvement showing moderate NED associated with more movement of the palate and lateral walls. E, Epiglottic collapse showing large NED and abrupt discontinuities in flow shape associated with lateral folding of the epiglottis. Note that pharyngeal pressure does not decrease as it does in panels A through D. Examples shown in D and E were taken from the same subject at different moments, highlighting the involvement of two different structures causing collapse in the same subject. Epi = pharyngeal pressure.

Another important observation was that epiglottic collapse often occurred suddenly and produced another flow shape defined as an abrupt discontinuity; this behavior was characterized by a rapid and severe reduction in airflow ($> 25\%$ reduction per 50 ms), followed by either constant, low, or immediate airflow recovery. Among the flow-limited breaths exhibiting epiglottic collapse, 76% (range, 20%-100%) showed an abrupt discontinuity (Figs 3E and 4, Video 5).

NED and the Structure of Collapse

Group data for NED in the different collapse categories are shown in Figure 5 and Table 1. NED was significantly different between the different groups ($P < .001$). Post hoc analysis showed that NED was

significantly lower among patients with tongue-related obstruction compared with patients with isolated palatal, lateral wall, or epiglottic collapse ($P < .01$). In addition, NED was significantly lower among subjects with isolated palatal collapse compared with epiglottic collapse ($P < .05$).

Noninvasive Tool to Estimate the Site of Collapse

In patients with a single predominant mechanism of collapse, it may be possible to infer some information about the pharyngeal structure causing collapse. A flowchart was developed to illustrate how this might be accomplished. Minimal NED ($< 34.4\%$) accurately defines tongue-related collapse. Severe NED and abrupt discontinuities in flow are characteristic of epiglottic

Figure 4 – Representative examples of epiglottic collapse taken from different subjects. Epiglottic collapse is characterized by severe negative effort dependence with and without abrupt discontinuities. Note that during unobstructed breaths, the epiglottis is not wide open and therefore may be more vulnerable to sudden obstruction.

collapse. Patients with moderate to severe NED without abrupt discontinuities can have either lateral wall or palatal collapse (Fig 6).

Discussion

This study demonstrates that when a single or predominant structure is found to cause collapse of the pharyngeal airway, it produces a recognizable effect on the pattern of inspiratory airflow limitation. A flat flow limitation pattern (small NED) is indicative of

Figure 5 – Negative effort dependence according to the pharyngeal structure causing collapse. * $P < .05$; ** $P < .01$; *** $P < .001$. Hollow dots represent seven subjects that have the epiglottis and an additional structure involved in collapse. Solid dots represent negative effort dependence of each subject according to the structure involved in collapse. Horizontal lines represent the medians of each group.

Figure 6 – Flowchart to identify the pharyngeal structure causing collapse. Small NED (< 34.4%) was able to detect tongue-related obstruction with a sensitivity of 100% and specificity of 92%. Patients with moderate to severe NED (> 34.4%) could have collapse at the lateral walls, palate, or epiglottis. An NED of $\geq 60.5\%$ was able to detect patients with epiglottic collapse with a sensitivity of 89% and specificity of 90%. In addition, the presence of discontinuities among patients with severe NED was able to identify patients with epiglottic collapse because all had abrupt discontinuities in flow. See Figure 3 legend for expansion of abbreviation.

tongue-related obstruction, whereas a scooped-out flow limitation pattern (large NED) suggests that the tongue is not likely contributing to pharyngeal obstruction, but rather collapse is because of one of the other pharyngeal structures. Epiglottic collapse is associated with severe NED and abrupt discontinuities in inspiratory flow. The importance of these findings is that the careful assessment of flow shape may prove to be an inexpensive and noninvasive way of determining the structure causing pharyngeal collapse.

The heterogeneous shapes of flow-limited breaths among patients with OSA have long been recognized.^{5-7,10} Aittokallio et al⁵ used an algorithm to classify nasal flow shapes taken from normal individuals and patients with OSA into seven different classes; however, they did not explore the mechanisms leading to different flow shapes. In the present study, we used NED to describe the variability in flow shapes. NED was associated with the subjective amount of phasic movement of the pharyngeal structure involved in obstruction (Fig 3). This is in line with our previous observations that NED is associated with changes in upper airway resistance.⁶ Therefore, a smaller phasic movement of the pharyngeal structure (as observed in tongue-related obstruction) is predicted to lead to a smaller change in upper airway resistance and a smaller NED.

Similar to previous studies, this study suggests there may be mechanical interactions between the tongue and palate.^{11,12} Using a thin pressure-sensing device inserted between the dorsum of the tongue and the anterior border of the palate, Isono et al¹¹ showed that in five out of 14 individuals, there was positive pressure, suggesting that the tongue was pushing against the palate. Isono et al¹¹ labeled these individuals as having a posteriorly located tongue to describe the effect of the dorsum of the tongue on the soft palate. We speculate that a posteriorly located tongue may stabilize the soft palate through surface adhesive forces and prevent phasic velopharyngeal narrowing in response to negative inspiratory pressure (small NED). In contrast, without close contact with the dorsum of the tongue, the soft palate may display greater posterior movement into the airway lumen in response to inspiratory negative pressures (isolated palatal collapse with large NED) (Figs 1, 3).

Previous studies have shown that identifying the site/structure of pharyngeal collapse in patients with OSA can improve the success rates of OSA therapy. Several studies have shown that uvulopalatopharyngoplasty is

most effective when pharyngeal obstruction is confined to the palate compared with when there is collapse at other sites within the airway.^{2,13-16} Furthermore, concentric collapse was shown to decrease the success of implantable airway stimulation.³ Finally, palatal collapse was independently associated with a positive response to mandibular advancement device therapy.⁴ These observations suggest that identifying the structures causing collapse may be helpful in selecting OSA therapy. Therefore, the analysis of flow limitation shapes may provide valuable information about the pharyngeal structure causing collapse and allow individualized OSA therapy.

The results of this study suggest that flow shape analysis could be used to identify epiglottic collapse, particularly because the discontinuity and large NED are easy to recognize. Epiglottic collapse has been observed among nonresponders to pharyngeal surgery, and it has been implicated as a cause of CPAP intolerance.¹⁷⁻¹⁹ A high prevalence of epiglottic collapse was found in the present report (29%), which is similar to previous endoscopy studies (11%-44%).^{4,20-22} Our observations of a characteristic inspiratory flow shape associated with epiglottic collapse (abrupt discontinuity and/or sudden appearance of severe NED) provide a noninvasive tool to detect epiglottic collapse.

Previous studies performed during sleep using endoscopy, CT scan, and MRI have shown that the pharynx can obstruct at more than one site.^{3,22-24} Vroegop et al²² performed drug-induced sleep endoscopy in 1,249 patients and showed that 68% had multilevel collapse. The most frequent combination was collapse of the palate and tongue base (26% of patients), followed by the palate and epiglottis (21% of patients). Huon et al²³ compared upper airway dynamic MRI findings during sleep among patients with mild and severe OSA. Multilevel collapse was observed in all patients with severe OSA but only 20% of patients with mild OSA. We observed that a combination of epiglottic collapse and either tongue, palate, or lateral walls were present in 23% of patients. Although the present study was not designed to investigate multisite collapse, the lower occurrence of multilevel collapse may be because of the following reasons. First, we used a different and somewhat simpler classification scheme than used in previous studies. For instance, instead of classifying anteroposterior palatal collapse and tongue base obstruction as different sites of collapse, we used tongue-related obstruction to describe collapse occurring at both the palate (tongue pushing the palate anteriorly) and

tongue base. This classification scheme allowed us to designate the structure (tongue) causing collapse. Second, we associated the endoscopic images with simultaneously measured airflow. Unlike other studies, we did not consider partial collapse of a given structure important unless it produced a recognizable decrease in flow. Simultaneous airflow has not been used in previous studies.^{3,22-24} Third, we used a small amount of CPAP in patients with cyclic obstructive apneas to increase end-expiratory pharyngeal dimensions and facilitate the distinction between the pharyngeal structures. CPAP was also used for similar reasons by Li et al²⁴ in a study using dynamic upper airway CT scan to determine the site of pharyngeal collapse during sleep. Finally, the use of sedation in previous studies^{3,22,24} may potentially have influenced the collapsibility of the pharynx.

The present study has some limitations. First, we used a sealed mask and pneumotachograph to measure airflow and a pressure catheter to quantify pharyngeal pressure, which are not used during clinical polysomnography. Therefore, additional studies comparing flow shape and NED from nasal cannula and pneumotachograph are necessary to apply the findings of the present study to clinical practice. Because flow signal as measured by nasal pressure cannulas has been shown to be very similar to pneumotachograph-measured flow,²⁵ airflow shape analysis from nasal pressure cannula may be feasible. Second, low levels of CPAP were used to facilitate stable flow limitation in two-thirds of the subjects of this study. We found that low levels of CPAP made isolation of a single collapsing structure possible. In reality, more than one collapsing structure may occur

in a particular patient. The third limitation is that NED could, depending on how it is defined, be influenced by pharyngeal luminal pressure and hence vary within a patient. We made sure that NED was measured under the influence of substantial negative pharyngeal pressure (-11 to -17 cm H₂O on average) where flow is typically flat. For this reason, future studies comparing NED with and without pharyngeal pressure monitoring should be performed before these results can be extended to clinical polysomnography. Fourth, the presence of a pharyngeal catheter itself may have influenced some of our observations. We feel this is unlikely given our observation that NED did not change when the pharyngeal catheter was removed during expiration in a subset of patients. Furthermore, a study showed that a pharyngeal catheter does not influence pharyngeal collapsibility.²⁶ Fifth, in this study we were not able to study the influence of pharyngeal muscle activity because of the already heavy instrumentation used. Finally, the application of nasal topical anesthesia might have influenced our results. However, we used a small amount of lidocaine through the nose, which has a very short duration of action. Previous observations from our group showed that pharyngeal anesthesia using a larger topical lidocaine dose did not influence airflow shape.²⁷

The novel observation of this study is that the pharyngeal structure causing collapse strongly influences inspiratory flow shape. This finding provides the foundation for noninvasive assessment of the pharyngeal structure causing collapse using flow shape analysis.

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Author contributions: P. R. G. had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis, including and especially any adverse effects. P. R. G., D. P. W., and A. W. contributed to conception and design. P. R. G., S. A. S., J. P. B., S. H. L., E. S. K., B. G. D., E. J. K., D. P. W., and A. W. contributed to acquisition, analysis, and interpretation. P. R. G., S. A. S., J. P. B., S. H. L., E. S. K., B. G. D., E. J. K., D. P. W., and A. W. contributed to drafting the manuscript for important intellectual content. P. R. G., S. A. S., J. P. B., S. H. L., E. S. K., B. G. D., E. J. K., D. P. W., and A. W. approved the current version of the manuscript and have agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Additional information: The e-Appendix and Videos can be found in the Supplemental Materials section of the online article.

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