Segmental analysis of nasal cavity compliance by acoustic rhinometry

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IN ADULT SUBJECTS BREATHING quietly at rest, the nose provides half of the airflow resistance of the entire respiratory tract. The anterior part of the nasal cavity, including the nasal valve area and inferior turbinate, is responsible for the larger portion of nasal resistance. The nasal valve is the narrowest segment of the nasal cavity, lying obliquely in the sagittal plane, bounded laterally by the caudal end of the upper lateral cartilage, medially by the septum, and ventrally by the inferior rim of the piriform aperture. Several millimeters beyond the structural components of the nasal valve, the anterior part of the inferior turbinate determines a functional component of erectile tissues characterized by a variable blood content of capacitance vessels. The anterior part of the nasal cavity is therefore a dynamic mucous-osseous-cartilaginous structure that should play an important role in nasal ventilation regulation. Variations in the lumen cross-sectional dimension of this functional nasal segment have a major impact on the magnitude of airflow resistance. For example, moderate narrowing of the anterior part of the nasal cavity can result in increased nasal resistance, inducing a switch from 100% nasal to oronasal ventilation, resulting in very uncomfortable nasal stuffiness for the patient. A common cause of nasal obstruction is collapse of the nasal valve area due to negative nasal pressures occurring during exercise or even during resting inspiration (nasal valve syndrome), because this structure often becomes weak and flaccid with aging or after surgical trauma (reduction rhinoplasty, lateral rhinotomy). The mechanical properties of the nasal wall, although important to provide a better understanding of nasal physiology and pathology, are poorly defined at the present time. Kesavanathan et al. measured regional differences in nasal pressure-volume relationships using acoustic rhinometry and a negative pressure applied to the nostril. They showed that the nasal valve and anterior part of the inferior turbinate exhibited morphological changes in response to negative pressure with differences before and after local application of decongestants.

Acoustic rhinometry has recently been validated as the best objective method to assess the configuration of the nasal airway. It provides measures of the nasal cross-sectional area and nasal volume as a function of the axial distance along the nasal passage. These measures are sensitive and reproducible in the proximal 5 cm of the rhinograph baseline distance. Acoustic rhinometric measures have been validated by computed tomography and magnetic resonance imaging. It has been shown to be a sensitive method to measure relative changes in the internal dimensions of the nasal cavity according to mucosal volume changes, particularly important in the turbinate area.
In this study, we used acoustic rhinometry and negative pressure applied to the nostril to assess the effect of negative pressure on internal nasal cavity geometry with particular emphasis on the various segments on the acoustic curve to describe more precisely the mechanical properties of the various structures of the anterior part of the nasal cavities (i.e., the nasal valve, anterior and medial parts of the inferior turbinate, and the middle meatus region).

We hypothesized that the anatomic components of the various segments of the nasal cavity determine tissue elastic characteristics and compliance, depending on the mucovascular volume of erectile tissues. Nasal wall compliance was defined as the nasal cross-sectional area-to-pressure ratio measured in the nasal cavity when a steady negative pressure was applied to the nostril. Negative pressure simulated the physiological condition of inspiration, which can result in collapse of nasal structures. We showed that the anatomic constitution of each segment of the anterior part of the nasal cavity determined their cross-sectional area and volume and consequently their compliance.

SUBJECTS AND METHODS

Subject Selection and Characterization

This study was performed in six healthy nonsmoking Caucasian volunteers (2 women, 4 men, mean age 37 yr). None of these subjects had a history of nasal complaints, nasal trauma, or nasal surgery, and they were not using any nasal medications that could modify nasal function and bias the results. All subjects had normal clinical and endoscopic examination of the nasal fossa. All measurements were performed only after the subject had acclimatized to the controlled environment measurement room for a 15-min period, in a comfortable upright seated position. For each subject, measurements were performed on the same day to avoid intraindividual variations.

Posterior Rhinomanometry

Nasal resistance was measured in all subjects by posterior rhinomanometry according to international recommendations (1, 5). Briefly, flow measurements were carried out by using a transparent nasal face mask fitted with a Fleisch no. 1 pneumotachograph (Lausanne, Switzerland) while the subject breathed through the nose. The pneumotachograph was connected to a pressure transducer (Validyne MP 45, Northridge, CA; ±2 cmH₂O). Oropharyngeal pressure was recorded via a catheter inserted through a hole drilled in the stopcock obstructing the cylindrical part of a modified mouthpiece, placed between the lower lip and the protruding tongue (5). One port of a differential pressure transducer (Validyne MP 45 ± 14 cmH₂O) was connected to the catheter of the mouthpiece, whereas the other port was connected to the nasal mask to allow transnasal pressure measurement.

For each subject, nasal resistance (total nasal resistance, right and left nasal resistances) was recorded three times in two different conditions, i.e., before and 10 min after nasal mucosal decongestion (MD) (0.05% oxymetazoline; one puff/ nostril). The average of the three measurements was used for analysis.

Nasal Geometry Measured by the Acoustic Reflection Method

For each subject, acoustic rhinometric measurements were performed on the nasal fossa exhibiting the lower resistance determined by posterior rhinomanometry before MD. Acoustic rhinometric measurements were performed several minutes after posterior rhinomanometry under the various conditions of nasal decongestion and pressure described below.

The longitudinal area profiles of the nasal cavity, A(x), were measured by use of the two-microphone acoustic reflection method, as previously described (15, 17). Briefly, the device consisted of two microphones (piezoresistive pressure transducers 8510-B; Endevco France, Le Pré Saint-Gervais, France) and a horn driver mounted on a wave tube (inner diameter 1.2 cm and overall length 22 cm) connected at one end to the nostril with a nosepiece, allowing tight closure of the nasal aperture without deformation of the nasal valve. The other end of the wave tube was connected to a steady negative-pressure generator (see Fig. 1). An acoustic wave was generated by the horn driver, which was driven by a personal computer via a digital-to-analog converter; microphone outputs were fed into an analog-to-digital converter (14 bits, 24-μs sampling period). These digitized data were analyzed to obtain the cross-sectional area of the nasal airway as a function of the distance along the longitudinal axis, with a spatial step increment ΔL ≈ 0.4 cm (see Fig. 2). Each acquisition sequence consisted of 10 consecutive acoustic waves generated at a frequency of 2.5 Hz, and it was achieved in apneic conditions. The mean of these 10 area-vs.-distance functions was stored for further analysis. During acoustic measurement, the steady pressure in the nasal cavity and in the wave tube was checked to ensure that there were no leaks with a U tube. If this pressure was not stabilized at the predetermined negative value, the acquisition sequence was rejected. We reset the electrical zero of the microphone output for each negative steady-pressure condition. More details on the theoretical foundation of the two-microphone method and its validity to estimate nasal cavity area under negative steady pressure can be found in the APPENDIX.

Two curves and computed dimensions were collected and averaged in the nasal cavity under each of the conditions described below.

Fig. 1. Diagram of the setup used to determine the area-to-pressure ratio. Acoustic pressure, resulting from a pulse generated by a horn driver, is recorded at two loci of a wave tube to infer longitudinal airway area profile, A(x). This area profile is measured for different steady negative pressures from 0 to −10 cmH₂O, allowing estimation of the area-to-pressure ratio.
Data Analysis

MCA, D-MCA, and segment analysis. The minimum cross-sectional area (MCA) and its distance from the nostril (D-MCA) were computed from the area-vs.-distance functions while the subject was breathing room air (atmospheric pressure).

Three segments of the nasal cavity were defined from D-MCA obtained with decongestant (D-MCA_{post}), i.e., 10 min after one puff of 0.05% oxymetazoline. Segment 1 was defined as the segment lying from D-MCA_{post} - 0.4 cm to D-MCA_{post} + 0.4 cm (see Fig. 2). The distance of 0.4 cm represents one spatial step increment, \( \Delta L \), determined by the spatial resolution of the acoustic rhinometric method. Segment 2 was defined as the segment lying from D-MCA_{post} + 2 \( \Delta L \) (0.8 cm) to D-MCA_{post} + 5 \( \Delta L \) (2 cm). Segment 3 was defined as the segment lying from D-MCA_{post} + 6 \( \Delta L \) (2.4 cm) to D-MCA_{post} + 9 \( \Delta L \) (3.6 cm).

Compliance analysis. Different steady pressures were applied to the distal end of the wave tube connected to the nostril, i.e., 0 = atmospheric pressure, \(-2, -4, -6, -8, \) and \(-10 \text{ cmH}_2\text{O} \) before and 10 min after MD (one puff of 0.05% oxymetazoline). Figure 3 shows an example of the area-vs.-distance curves obtained under the various conditions.

Compliance for segments 1, 2, and 3 was defined as the ratio between the variation of area and the variation of steady pressure applied to the nasal cavity. Compliance was defined by the ratio between area and pressure rather than the ratio between volume and pressure, because this definition allowed comparison of the mechanical properties of the wall between segments of different lengths. The relationship between area and pressure was found to be linear over the pressure range tested from 0 to \(-10 \text{ cmH}_2\text{O} \) for the three segments (see RESULTS). Compliance was therefore computed as the slope of the line \( A = C \cdot P \) fitting the set of \( (A, P) \) data using a least square error method, where \( A \) is area, \( C \) is compliance, and \( P \) is pressure.

For each subject, the acoustic curves were recorded twice under each pressure condition, and the mean computed area was used for analysis. The acoustic curves were systematically allowed to return to baseline conditions (atmospheric pressure) before each change in negative pressure, from 0 to \(-10 \text{ cmH}_2\text{O} \).

Statistical analysis. Comparisons between the three segments were performed by using the Kruskal-Wallis H test. The limit of significance was defined as \( P = 0.05 \). Post hoc comparisons were performed by using a Wilcoxon test looking for statistically significant differences between two groups. A Wilcoxon test was used to compare parameters (MCA, D-MCA) before and after MD.

RESULTS

Table 1 shows the subject characteristics with respect to age, gender, ethnic background, and unilateral nasal airflow resistance of the nasal fossa selected for the study. All subjects had normal unilateral nasal airflow resistance under baseline conditions and after MD.

Figure 3 shows a typical area-vs.-distance curve of a normal decongested nasal cavity, obtained with the acoustic rhinometric method. MCA changed significantly after MD \( (0.63 \pm 0.27 \text{ cm}^2 \text{ before MD}; 0.74 \pm 0.2 \text{ cm}^2 \text{ after MD}, \text{i.e., 18\% increase}) \). In all subjects, D-MCA systematically shifted anteriorly by one acoustic spatial step increment after MD, i.e., by 0.4 cm.

<table>
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<th>Subject No.</th>
<th>Age, yr</th>
<th>Gender</th>
<th>UNR baseline, cmH_2O^{-1/s}</th>
<th>UNR Decongested, cmH_2O^{-1/s}</th>
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<td>Female</td>
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<td>2.2</td>
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</table>

UNR, unilateral nasal airflow resistance measured by posterior rhinomanometry.
Before MD, the average area of segment 1 under the various conditions of steady pressure was lower than the average area of segments 2 and 3 (the area of segment 2 was 28% greater than that of segment 1, and the area of segment 3 was 100% greater than that of segment 1). The average area of segment 1 under the various conditions of steady pressure was not significantly different before and after MD. After MD, the average area of segment 1 was still significantly less than that of segments 2 and 3 (the area of segment 2 was 63% greater than that of segment 1, and the area of segment 3 was 136% greater than that of segment 1) (Fig. 4).

The relationship between area and pressure was linear over the pressure range tested, from 0 to $-10 \text{ cmH}_2\text{O}$, for the three segments (Fig. 4).

The nasal area-to-pressure ratio (compliance) of the nasal valve was observed for the anterior part of the nasal cavity (Figs. 4 and 5). Before MD, the compliance of segment 1 was significantly lower than the compliance of segments 2 and 3 and the compliance of segment 2 was significantly lower than the compliance of segment 3 (compliance was $0.031 \pm 0.016$, $0.045 \pm 0.024$, and $0.056 \pm 0.029 \text{ cm}^2/\text{cmH}_2\text{O}$ for segments 1, 2, and 3, respectively). After MD, compliances decreased and the compliance of the three segments became similar (compliance was $0.025 \pm 0.006$, $0.024 \pm 0.012$, and $0.023 \pm 0.021 \text{ cm}^2/\text{cmH}_2\text{O}$ for segments 1, 2, and 3, respectively) and were no longer significantly different (Fig. 5).

**DISCUSSION**

Our study in healthy subjects demonstrated that nasal wall compliance, derived from acoustic rhinometry, increased progressively with distance from the nostril. This variation of compliance disappeared after nasal MD. From these results, it can be inferred that the first 5 cm of the acoustic rhinometric curve of the nasal cavity can be divided into three regions: 1) the nasal valve, which showed no change in compliance after MD; 2) the anterior and medial parts of the inferior turbinate region; and 3) the middle meatus, which showed increasing changes in compliance after MD in line with the increasing amount of erectile tissue.

**Segmental Analysis of the Acoustic Rhinometric Curve**

Acoustic rhinometry provides a minimally invasive, convenient, and accurate method to measure the di-
dimensions of the nasal airway, which is particularly useful for assessment of mucovascular status (2). Reliable data can only be obtained over the proximal 5 cm of the acoustic rhinometric curve, because of the presence of the paranasal sinuses in the posterior part of the nose, which constitute a distal source of error for measurements (11). Although acoustic rhinometry has been used in clinical practice for many years, no consensus has been reached concerning interpretation of acoustic rhinometric curves in terms of the corresponding anatomical structures, including the nasal valve defined by Cole (3) as the structure anterior to the anterior tip of the inferior turbinate. Two notches are usually observed in the first 2 cm of the curve, and it has been suggested that the MCA is representative of the head of the inferior turbinate (19). However, such findings may be different in patients and healthy subjects. Our data indicate that, in healthy subjects, the MCA is more representative of the nasal valve region and not of the inferior turbinate for two reasons. First, the increase in MCA was minimal after decongestant. This small but significant effect of oxymetazoline on the nasal valve can be explained by the presence of erectile tissue on the septal nasal wall (2). If the inferior turbinate were a structural component of the nasal valve, intranasal application of oxymetazoline should be responsible for a marked increase in the dimensions of the MCA, as observed in patients with mucosal abnormalities (20). Second, the distance from the nostrils to the MCA, which was 1.8 cm, in agreement with previous studies (2, 19), changed by only 0.4 cm on the acoustic curve after decongestant application. If the inferior turbinate region was included in the MCA of healthy subjects, MCA position should markedly shift anteriorly after oxymetazoline, as observed in turbinate hypertrophy mucosal (7, 20).

Beyond the nasal valve region analyzed in segment 1 on the acoustic curve, the turbinates are the major determinants of the nasal cross-sectional area in healthy subjects. On endoscopic examination of the nasal cavity, the head and middle part of the inferior turbinate are located just posterior to the nasal valve. To study the inferior turbinate region, we therefore defined a second segment on the acoustic curve from 0.8 to 2 cm from the MCA. Approximately 4 cm posteriorly to the nostril, i.e., 2 cm from the MCA, in the middle meatus region, the middle turbinate began to be superimposed on the inferior turbinate, defining a third segment on the acoustic curve from 2.4 to 3.6 cm from the MCA.

Nasal Wall Compliance

Nasal wall compliance was determined by application of a negative pressure to the nasal cavity. Our study demonstrated that nasal wall compliance increased progressively from the proximal nasal segment to the distal segment.

The compliance measured in the nasal valve region was the lowest value determined in the anterior part of the nasal cavity, in agreement with the results of Kesavanathan et al. (14). In this study, as in our own study, it is surprising that the nasal valve wall, composed of distensible structures (tissue elastic structures of the alae nasi and facial muscles of the nose) had the lowest compliance of the anterior part of the nasal cavity. Furthermore, collapse of the nasal valve is believed to be a common cause of nasal obstruction, especially during exercise when a high negative pressure is generated by forced inspiration at the entry of the nasal cavity (18). Nevertheless, the nasal valve region has the narrowest cross-sectional area of the nasal cavity and is considered to be responsible for half of the airflow resistance of the entire respiratory tract (19). These findings suggest that the nasal valve in healthy subjects represents the flow-limiting segment of the nasal cavity because of its narrow cross-sectional area and not because of a high compliance. However, determination of nasal valve compliance may help to characterize nasal valve dysfunction in patients complaining of nasal valve collapse.

A major result of the present study is that the inferior and middle turbinates presented a higher compliance than the nasal valve region, although the turbinates are located within a nondistensible bony cavity. This high compliance is probably related to mucosal blood volume and the quantity of vascular tissue lining the bony turbinates. These results suggest that congested and hypertrophied turbinates would have a high compliance and would be easily deformed by application of a negative pressure to the nostril. This hypothesis is confirmed by the observation that compliance became similar in the three segments of the anterior part of the nasal cavity after application of oxymetazoline to the nasal cavity. Oxymetazoline is an α-adrenergic agonist known to reduce blood volume by acting on capacitance vessels of the cavernous plexus located in the vascular tissues of the turbinates. It can be postulated that the volume of vasoerectile tissue is considerably reduced after oxymetazoline and no longer influences nasal wall compliance. It must be stressed that, after MD, the nasal wall compliance of the two turbinate segments became similar to that of the first segment corresponding to the nasal valve region.

The study by Kesavanathan et al. (14) was also designed to characterize the nasal volume-to-pressure ratio in the nasal cavity. This ratio was found to decrease in the region distal to the nasal valve after decongestant but was still much higher that that of the nasal valve region, in contrast with our results. This apparent discrepancy can be explained by the fact that Kesavanathan et al. analyzed volume-to-pressure ratio, whereas we studied the area-to-pressure ratio. Unlike the volume-to-pressure ratio, the area-to-pressure ratio is an index that can be used to compare two segments with two distinct lengths, because it provides a value per unit length. Moreover, Kesavanathan et al. analyzed the acoustic curve to 10 cm posterior to the nostrils, but it is now recommended to limit interpretation of acoustic rhinometric curve to the first 5 cm of the nasal cavity (2). In our study, we chose to analyze
only the anterior part of the nose to limit the risk of error, because of the presence of the paranasal sinuses in the posterior part of the nasal cavity.

In summary, our study allowed partitioning of the nasal cavity into physiologically distinct areas: the nasal valve area, the anterior and middle parts of the inferior turbinate, and the middle meatus region. It also suggests that assessment of nasal wall compliance in the turbinated region may help to define the state of congestion of the nasal mucosa and consequently the degree of turbinate mucosal hypertrophy, which is very difficult to evaluate clinically. Analysis of the nasal cross-sectional area-pressure relationship in the anterior part of the nasal cavity, by providing a more accurate measure of the mechanical properties of the nasal wall, will allow improved analysis of nasal physiology, providing a better understanding of various nasal diseases characterized by tissue changes, such as variability in vascular tone, mucous edema, and postoperative remodeling of the nasal wall (nasal valve collapse). Nasal wall compliance measurement would be a useful and accurate method to analyze the nasal cycle, changes in mucovascular status observed during various forms of rhinitis (especially in the case of vasomotor dysfunction) and after nasal exposure to atmospheric pollutants, allergens, and so on. A better understanding of nasal pathophysiology is probably the key step to improving the treatment of these diseases.

APPENDIX

The acoustic reflection method is based on the fact that the longitudinal cross-sectional area profile along the airway, $A(x)$, can be inferred from broadband reflection impulse response of the airway, $h(t)$, under a set of restrictive but workable conditions (21). Here, we used the two-microphone method (17) to measure $h(t)$. In this method $h(t)$ is obtained from the measurement of the pressure in two loci of a wave tube

$$h(t)[p(0,t) - p(L,t - \tau)] = p(L,t + \tau) - p(0,t) \quad (A1)$$

where $t$ is the time and $p$ is the “acoustic” pressure. The asterisk denotes the convolution integral; 0 and $L$ designate the spatial coordinates of the two pressure measurement loci; and $\tau$ is the propagation delay of the pressure wave between the two sites of measurement. The $h(t)$ can be determined from this equation by using a variety of deconvolution algorithms if both $p(0,t)$ and $p(L,t)$ are known. The use of Eq. A1 requires accurate knowledge of the propagation delay. Because the wave propagation in the wave tube is assumed lossless, the early portions of the recorded pressure at the two measurement sites are identical except for the propagation delay. This propagation delay is determined by comparing the two microphone outputs in the early part of their respective transients. As a consequence, the two-microphone method does not require a precise knowledge of the gas thermodynamic characteristics because the method implicitly includes the measurement of the wave delay propagation between the two microphones. In fact, the method is not affected by the characteristics of the gas as long as it agrees with the lossless one-dimensional wave propagation assumption. It was experimentally confirmed (16) when the area of a glass tube model measured when using air was almost superimposable to the ones obtained when using an 80% He-20% O2 mixture. By comparison with air, using He-O2 increases the wave speed and propagation delay (~87%). By contrast, in the present study the $-10 \text{ cmH}_2\text{O}$ pressure induced a increase of the wave speed less than 0.002%.

Equation A1 requires only the knowledge of the “acoustic” pressure, i.e., the AC pressure. The DC pressure, i.e., the steady pressure, is not used in this equation and does not influence the terms of this equation as long as we are able to separate DC and AC pressure in our measurements. To ensure this separation for each steady pressure condition, the reset of the electrical zero of the microphone output was associated with a digital DC filter in the software.

It is known that the area inferred with the acoustic method behind large variation of area (constriction and aperture) may be more or less erroneous. Therefore, this artifact may jeopardize the validity of the inferred area segment 2 and 3, especially when segment 1 is the most constricted, as shown in Fig. 3 for a $-10 \text{ cmH}_2\text{O}$ steady pressure. The importance of this artifact depends on many factors, such as maximal area variation, geometry of the inlet, type of deconvolution algorithm, type of filter, and so on. To validate our measurement, we used a Plexiglas model in which the internal area was close to the area measured in the nose. We simulated constricted area in the first part of this model with some modeling clay. Then we compared the area of the second part (unmodified) of the model, measured with the acoustic method, for the different conditions of constriction. The measurement made without constriction was considered here as the reference measurement. Two levels of obstruction were simulated. The first level corresponded to the cross-sectional area observed in segment 1 at atmospheric pressure, whereas the second level corresponded to the constriction observed in segment 1 at $-10 \text{ cmH}_2\text{O}$ steady pressure. We did not observe any discrepancy between the different area curves of the second part of the model beyond the obstruction (see Fig. 6).

![Fig. 6. Area vs. distance of a Plexiglas model behind a constriction inferred by the acoustic reflection method. Two levels of constriction were simulated, corresponding to the MCA observed in nasal cavity at atmospheric pressure (•) and $-10 \text{ cmH}_2\text{O}$ steady pressure. Results were compared with those obtained when there was no constriction considered as the reference (×).](image-url)
These results showed that the artifact associated with measurements behind constricted areas was negligible for our nasal cavity measurements.

REFERENCES