Acoustic Rhinometry: Accuracy and Ability to Detect Changes in Passage Area at Different Locations in the Nasal Cavity

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Objectives: To evaluate the accuracy of acoustic rhinometry (AR) measurements, and to assess how well AR detects obstructions of various sizes at specific sites in the nasal cavity, we created a cast model from an adult cadaver nasal cavity.

Methods: The actual cross-sectional areas of the cast model nasal passage were determined by computed tomography and compared with the corresponding areas measured by AR. To assess how nasal obstruction affects the AR results, we placed small wax spheres of different diameters at specific sites in the model (nasal valve, head of the inferior turbinate, head of the middle turbinate, middle of the middle turbinate, choana, and nasopharynx).

Results: The AR-derived cross-sectional areas in the first 6.5 cm of the cast model nasal cavity were very close to the corresponding areas calculated from computed tomographic sections perpendicular to the presumed acoustic axis. However, AR overestimated the passage areas at locations posterior to the 6.5-cm point. Acoustic rhinometry gave an accurate indication of the passage area of the nasal valve and its distance from the nostril. The nasal valve and the choana were indicated by significant dips on the AR area-distance curve, whereas the curve was smooth throughout the region that included the head of the inferior turbinate, the head of the middle turbinate, the middle of the middle turbinate, and the nasopharynx. In other words, AR did not discretely identify these latter sites. Acoustic rhinometry detected the different-sized inserts (obstructions) more accurately at the nasal valve than at sites posterior to this location.

Conclusions: The results of the study show that AR is a valuable method for assessing the anterior nasal cavity. This technique is sensitive for detecting changes in passage area at the nasal valve region; however, the sensitivity is lower at sites posterior to this. The findings suggest that when there is substantial narrowing of the nasal valve, AR will not identify an obstruction at any location posterior to the nasal valve. In such situations, AR measurements beyond the abnormal nasal valve may easily lead to misinterpretation of the patient’s nasal anatomy or condition.

Key Words: acoustic rhinometry, cast model, computed tomography, curved acoustic axis, nasal cavity.

INTRODUCTION

For more than a century, rhinologists have been searching for a reliable way to evaluate the nasal airway in a wide range of patients. In 1989, Hilberg et al. introduced acoustic rhinometry (AR) as an objective method for examining the nasal cavity. This technique is based on the principle that a sound pulse propagating in the nasal cavity is reflected by local changes in acoustic impedance. Acoustic rhinometry is a quick, painless, noninvasive method that can be used to estimate the dimensions of nasal obstructions, evaluate nasal cavity geometry, monitor nasal disorders, and assess surgery results and response to medical treatment. Because of these advantages, AR has been widely accepted in a short period of time. However, lack of standardization is one of the main problems with this method, and the role of AR in the clinic is currently being evaluated.

In order to correctly interpret AR results, it is essential to know how certain anatomic structures in the nasal cavity are reflected on the AR area-distance curve, and thus be able to identify their locations on this curve. However, inconsistency in the literature has caused confusion. Different terms have been used to denote the same anatomic structure in the nose, and different names have been proposed for corresponding cross-sectional areas on AR curves. It should also be noted that AR actually measures cross-sectional area as a function of distance (from the nostril into the nose) along an estimated acoustic axis that passes through the center of the curved nasal airway, as opposed to a straight line parallel to the floor of the nose. This curved course of the nasal cavity complicates the interpretation of AR data.
and raises questions about the validity of comparisons between nasal cavity dimensions obtained by AR and those derived from computed tomography (CT) or magnetic resonance imaging. Most published studies have not considered this curved shape of the nasal cavity and acoustic pathway, and this neglect could lead to misinterpretation of AR results.7,12-14 Moreover, recent experimental and theoretical studies of pipe models simulating nasal passage anatomy have demonstrated that certain factors inherent to the physics and algorithms used in AR limit the accuracy of this method, and lead to systematic measurement errors.15-20 Nevertheless, the results of these pipe model studies still need to be confirmed with AR measurements of more realistic nasal cavity models.21 Finally, the literature contains very little information about the accuracy and sensitivity of AR measurements at different locations within the nasal cavity.1,2,22-23 Thus, there is also a need to examine how changes in the dimensions of different parts of the nasal cavity influence the accuracy of AR measurements.

The aims of this study were to evaluate the accuracy of AR measurements and to assess how well this method detects obstructions of various sizes at specific sites in the nasal cavity. To carry out the investigations, we used a cast model of an adult cadaver nasal cavity. We measured the actual cross-sectional areas of the cast model using CT and then compared these with AR-derived areas. Then we placed small wax spheres of different diameters at specific locations within the cast model. These sites corresponded to the nasal valve, the head of the inferior turbinate, the head of the middle turbinate, the middle of the middle turbinate, the choana, and the nasopharynx. We reviewed the previously proposed definitions for these anatomic structures in the nose, and attempted to identify their locations on the AR area-distance curve. The acoustic properties of our cast model are not identical to those of a vital nasal cavity, but investigation with this type of nasal passage model can provide useful information about the value of AR in the clinical setting.1,11,21

MATERIALS AND METHODS

A cast model of a human cadaver nasal cavity was made as follows. A luminal impression was prepared by injecting the right nasal passage of an adult cadaver with silicone (RTV-50, Rhone-Poulenc, Saint Fons, France). The material was allowed to set and was then removed from the nose by dissection. This luminal impression (Fig 1) was then used to cast a nasal cavity model (Fig 2). The walls of the cast nasal passage model were prepared from plaster material. The posterior portion of the cast model passage-way beyond the choana was rasped to enlarge the contracted cadaver nasopharyngeal cavity to normal adult dimensions. To prevent acoustic leakage and random user-related errors, we molded the plaster material anterior to the cast model nostril to form a cylindrical guide, thus ensuring that the nosepiece of the acoustic rhinometer fit tightly to the model (Fig 2).
First, to evaluate the accuracy of AR measurements at specific locations in the nasal cavity (see details below), we initially compared CT-derived and AR-derived area-distance curves for the cast model with no insert in place. In addition to examining for differences between these curves, we looked for changes within each curve (ie, whether the area measurements with either method distinguished the sites of interest in the study). The distance from the nostril (at 0.0 cm) to each of the designated sites inside the passage model (X0) was measured along the estimated acoustic axis (Fig 2). The distances recorded for the sites of the nasal valve, head of the inferior turbinate, head of the middle turbinate, middle of the middle turbinate, choana, and nasopharynx were 2.0, 2.8, 4.0, 5.8, 8.8, and 10.0 cm, respectively. These were all in excellent agreement with the corresponding distances determined from CT of the luminal impression.

Second, to assess AR detection of simulated nasal disorders, we inserted wax spheres of various diameters at specific locations in the cast model. The 7 sites of sphere placement chosen were based on previous definitions of the locations of important nasal cavity structures: the nostril and the 6 sites of interest inside the passage listed above. A set of 5 spherical inserts (diameters 0.3, 0.5, 0.7, 0.9, and 1.1 cm) was tested at each of these sites of interest in the model. For each set of AR measurements, the inserts were placed in sequence (from smallest to largest) at each designated site. To assess whether AR was able to detect simulated nasal disorders at the 7 locations, we placed the 5 different inserts one by one at each site and recorded the AR area-distance curve for each insert size (ie, a set of 5 AR area-distance curves per site). If there was a measurable difference within the set of areas recorded for any particular site, this was considered successful detection of the insert at that location.

A transient-signal acoustic rhinometer (Ecco Vision, Hood Instruments, Pembroke, Massachusetts) was used to perform the acoustic measurements. The processed bandwidth for this rhinometer ranged from 100 Hz to 10 kHz, and a 10-kHz low-pass filter was used to reduce the errors associated with cross modes in the actual nasal cavity. The same nosepiece was used to obtain all measurements presented in this article. All AR measurements were repeated at least 5 times to ensure that the results were reproducible. Data collected from the examinations were analyzed with Origin software (version 7.0, Microcal Software Inc, Northampton, Massachusetts).

Actual cross-sectional areas for the first 8.8 cm of the cast model nasal passage (ie, from nostril to choana) were determined from a CT scan of the luminal impression of the cadaver nasal passage. The CT examinations were performed with a multislice scanner (Somatom Sensation 16. Siemens, Erlangen, Germany) with tube voltage of 120 kV and current of 240 mA. The window width was 4,000 Hounsfield units, and the window level was centered at 600 Hounsfield units. Axial CT slices parallel to the long axis of the luminal impression of the cadaver nasal cavity were obtained with 0.75-mm collimation, 2-mm slice thickness, and 5-mm table feet, and these images were reconstructed with 1-mm intervals by means of a soft tissue algorithm. From the reconstructed axial slices, a 3-dimensional (3-D) shaded surface display image of the luminal impression was obtained (Fig 1).

As described in previous studies, the conceptualized acoustic axis for the AR determinations follows an estimated line that passes through the center of the nasal passage, and AR-derived distances from the nostril to sites along this line would be the same irrespective of passageway shape. To determine the cross-sectional areas perpendicular to the estimated acoustic axis, we divided the acoustic pathway of the luminal impression of the cadaver nasal passage into 2 segments and drew each manually in a 3-D reconstructed image (Fig 1). The first segment was in the anterior nasal cavity and formed a quarter-circle; it extended from the center of the nostril opening and ended at the head of the inferior turbinate. The second segment of the acoustic axis was drawn as a straight line parallel to the long axis of the inferior turbinate; it extended from the end point of the first axis segment to the choana. The length of each segment of the acoustic axis was measured on CT, and 30 slices perpendicular to the acoustic axis were obtained for each segment (ie, 60 cross-sectional areas recorded for the first 8.8 cm of the model nasal passage). A plot of the slice area versus the distance along the estimated acoustic axis yielded the CT-derived area-distance curve.

RESULTS

Figure 3 shows a graphic comparison of the actual cross-sectional areas of the cast model (determined from CT of the luminal impression) and the corresponding AR-derived cross-sectional areas. The AR data were in good agreement with the CT data through the first 6.5 cm of the cast model passage. For the nasal valve (the narrowest part of the nasal passage), the AR and CT evaluations yielded almost identical data for cross-sectional area (passage area; 1.08 cm²) and location relative to the nostril (2.0 cm). The results indicate that in cases in which the passage area of the nasal valve is in the normal adult range, AR measurements of the anterior nasal cavity
are precise. In contrast, at distances farther than 7.0 cm inside the nostril, the AR-derived cross-sectional areas were overestimated as compared to those obtained from CT. The degree of this area overestimation increased with distance, and was extremely high (about 70%) at the location of the choana (8.8 cm).

Careful inspection of Fig 3 reveals that the AR-derived area-distance curve was fairly smooth through the part of the nasal passage that includes the head of the inferior turbinate (site 3 in Fig 3), the head of the middle turbinate (site 4), and the middle of the middle turbinate (site 5). In other words, AR did not distinctly identify any of these structures. For the head of the inferior turbinate, the same held true on the CT-derived curve. At the location of the head of the middle turbinate, slight decreases in slope were noted on both curves. On both the CT and AR curves, the choana (site 6 in Fig 3) was reflected as deep minima; however, as noted, AR overestimated the cross-sectional area at the choana by about 70%. These findings suggest that even when the nasal valve passage area is in the normal adult range, AR only discretely identified the locations of the nasal valve and the choana.

Figure 4 illustrates the set of AR-derived area-distance curves that correspond to the cast model with an unobstructed nostril and with spherical inserts of 4 different diameters (d) placed at the nostril. The AR-measured cross-sectional area at the site of the nostril decreased from 0.9 to 0.4 cm² as the diameter of the insert increased from 0.3 to 0.9 cm. These results confirm that the first minimum on the AR area-distance curve (site 1 in Fig 3) corresponds to the junction between the end of the nosepiece of the acoustic rhinometer and the nostril.

In the next sets of experiments, we examined the cast model with spherical wax inserts of diameter d placed at specific distances (X₀) from the nostril. As noted, this simulated a disorder at different sites within the nasal passage. Figure 5 shows sets of AR area-distance curves for the cast model with inserts located at X₀ of 2.0 (nasal valve), 2.8 (head of inferior turbinate), 4.0 (head of middle turbinate), 5.8 (middle of middle turbinate), 8.8 (choana), and 10.0 cm (nasopharynx). Each set contains 6 curves: one corresponding to no insert and one for each of the 5 insert sizes. One feature common to all of the data sets presented in Fig 5 is that regardless of insert location, the AR-measured cross-sectional areas anterior to the obstruction were similar and almost completely independent of the size of the obstruction. The results suggest that in a cast model, regardless of the degree of obstruction, AR yields similar cross-sectional areas from the nostril to approximately 1.0 cm before the obstruction. The data also show that beyond a large obstruction in the nasal passage, AR underestimates cross-sectional area. The degree of area underestimation depends on both the diameter and the location of the insert.

The same group of graphs (Fig 5) reveals that AR was more sensitive in detecting different-sized spherical inserts placed at the nasal valve than in detecting inserts at more posterior sites. The AR area-distance curve obtained with the 0.3 cm diameter insert
placed at the nasal valve of the model was almost identical to that for the model without an insert (Fig 5A). This is because the effective cross-sectional area of this particular insert was very small (0.07 cm²) and therefore did not significantly reduce passage area at this location. However, when inserts of 0.5 cm diameter or larger were placed in the nasal valve, the AR-derived area of the nasal valve decreased sub-
When inserts were placed in locations posterior to the nasal valve, the sensitivity of AR in detecting changes in passage area decreased. Whereas AR detected the 0.5 cm diameter insert at the head of the middle turbinate, the smallest inserts that could be detected at the head of the middle turbinate, the middle of the middle turbinate, and the choana were 0.7, 0.9, and 0.9 cm, respectively (Fig 5A).

In summary, the findings from this part of the study indicate that when the nasal valve region is significantly narrowed, AR will not detect disorders at sites beyond this region.

DISCUSSION

None of the research done to date has established how well AR-measured cross-sectional areas correlate with actual areas in certain regions of the nasal cavity. Use of different terminology for a given anatomic structure in the nose causes confusion when one is locating its site on an AR area-distance curve. The rhinology literature has introduced various names for key anatomic sites in the nose. For example, the term “ostium internum” has been proposed as a counterpart to “ostium externum” for denoting the nostril or naris. Previously, Huizing discussed the nasal nomenclature that should be abandoned and replaced by anatomically, linguistically, and surgically correct terms. He suggested using the term “nasal valve area” for the narrowest region of the breathing pathway instead of “isthmus nasi” or “ostium internum.”

Lenders and Pirsig described the first such low point on the AR curve as the “I-notch” (I = isthmus) and noted that this corresponded to the functional isthmus nasi (nasal valve). They identified the second low point as the “C-notch” (C = concha) and noted that this corresponded to the head of the inferior turbinate. Lenders and Pirsig found that in AR of control subjects, the I-notch consistently indicated the overall smallest cross-sectional area. In contrast, they observed that in patients with turbinate hypertrophy (due to allergic or vasomotor rhinitis), the overall smallest cross-sectional area was the C-notch. In line with this observation, they referred to the 2-notch section of an AR curve in which the lowest notch corresponds to the isthmus nasi as a “climbing-W” and to the opposite situation (lowest notch denoting the head of the inferior turbinate) as a “descending-W.” The same authors reported that for patients with turbinate hypertrophy, the AR trace changes from a descending-W (characteristic of rhinitis and turbinate hypertrophy)
before decongestion to a climbing-W (more characteristic of normal subjects) after decongestion. According to Lenders and Pirsig, these 2 AR curves were identical at the isthmus nasi, reflecting the absence of nasal mucosa in this anatomic location. They noted that the 2 AR curves separated at a point corresponding to the anterior inferior turbinate because of the presence of congested nasal mucosa starting at this site.

In AR of 21 patients with septal deviation, Grymer et al identified the narrowest part of the nose as the isthmus nasi and noted that this structure was located slightly more posteriorly than the anatomic ostium internum. According to these authors, the isthmus nasi had the overall smallest cross-sectional area before decongestion and the ostium internum had the overall smallest cross-sectional area after decongestion. In a later study of healthy subjects with no gross nasal disorders, Grymer et al noted that the lowest point on the AR curve (site of smallest cross-sectional area) was the head of the inferior turbinate before decongestion and that the lowest point shifted to the site reflecting the isthmus nasi after decongestion.

Hamilton et al reported that the first low point (minimum) on the AR curve always corresponded to the same distance from the start of the acoustic pathway and also noted that its location was not affected by acoustic leakage through the gap between the nosepiece and the nose. They attributed the first minimum to the junction between the nosepiece and the nostril, as opposed to correlating it with nasal anatomy alone. Tomkinson and Eccles also interpreted the first low point, or minimum (M1), as the junction of the nosepiece with the nasal aperture, since they found that its location on the AR curve depended on nosepiece length. These authors concluded that the first minimum on an AR curve did not reflect an anatomic entity (and should be strictly interpreted as corresponding to the end of the nosepiece) and that the second minimum (M2) represented the nasal valve area. The same article noted that the inferior turbinate might contribute to the magnitude of the second minimum.

The results from the present study of variations on a cast model of the nasal cavity confirm the interpretations in 2 previous reports: the first minimum on the AR area-distance curve corresponds to the junction between the end of the nosepiece and the cast model nostril, and the second corresponds to the nasal valve. A similar interpretation may apply to the actual nasal cavity, although the acoustic properties of the cast model are not identical to those of a vital nasal cavity, and the geometry of the actual nasal cavity is somewhat more complicated than the model we investigated. However, Hilberg et al argued that the complex geometry of the actual nasal cavity does not significantly affect AR measurements.

In addition, our present study showed that anatomic structures posterior to the cast model nasal valve (ie, the head of the inferior turbinate, the head of the middle turbinate, the middle of the middle turbinate, and the nasopharynx) were not distinguishable on the AR curve. Possible explanations for this result may be the limited spatial resolution of AR and the fact that AR is not able to reflect sharp changes in cross-sectional area throughout the course of the nasal passage. Furthermore, previous model studies demonstrated that the accuracy of AR measurements diminished at locations beyond a significant constriction at the nasal valve. These findings suggest that disorders that narrow the anterior nasal passage, such as septal deviations, polyps, tumors, webs, strictures, or the nasal valve of a pediatric patient, may significantly affect the AR measurements when equipment intended for adults is used. Therefore, for patients with such conditions, the value of AR for evaluating the entire nasal cavity is limited.

In a clinical study that involved magnetic resonance imaging, Corey et al described valleys (or dips) on the AR curve that represented reductions in cross-sectional area at specific distances from the interface, each corresponding to defined anatomic structures in the nose. The authors suggested that the first, second, and third valleys (with respective cross-sectional areas CSA1, CSA2, and CSA3) on the AR curve represented the nasal valve, the anterior end of the inferior turbinate, and the anterior end of the middle turbinate, respectively. However, in that study, the magnetic resonance images were taken perpendicular to the floor of the nose. Later, Corey et al compared AR with rigid endoscopy for assessing landmarks in the nasal cavity. In the examinations, they touched the tip of the endoscope to a landmark and then measured the distance from the endoscope tip to the marking. With this method, they found that CSA2 and CSA3 corresponded to the anterior portions of the inferior and middle turbinates, respectively. Corey et al suggested that AR gives a good indication for cross-sectional areas CSA2 and CSA3, but does not clearly delineate the anatomic correlate of CSA1 (the nasal valve). However, in the original study that described the AR technique, Hilberg et al emphasized that the major problem with comparing AR findings to those from imaging techniques is that it is difficult to obtain data exactly in the same plane. Later, using a plastic nose model produced by stereolithographic techniques from a 3-D magnetic resonance imaging scan, Djupesland and Rotnes found good agreement between the nasal cavity volumes determined from
AR-derived dimensions and magnetic resonance imaging when the magnetic resonance cross sections were obtained perpendicular to the presumed course of the sound pathway. More recently, Cakmak et al. showed that when AR data for the nasal valve region are to be compared with calculations based on any imaging technique, the imaging cross sections must be taken perpendicular to the curved acoustic axis. They found a significant correlation between AR data and data from CT images obtained perpendicular to the curved acoustic pathway; however, there was no correlation between AR data and data from CT imaging done perpendicular to the nasal floor. Our present findings confirm the results of previous studies that emphasize the importance of the curved acoustic axis; that is, distances on AR curves correspond accurately to distances within the nasal passage as measured along the estimated acoustic pathway. Our results also show that it is not appropriate to make critical statements about the validity of AR on the basis of CT or magnetic resonance imaging data from different imaging axes. Previous studies not taking into account the curved shape of the nasal cavity could lead to misinterpretation of AR data.

Various imaging methods have been used to test the accuracy of AR in clinical trials with healthy human subjects. These have revealed significant correlations between the cross-sectional areas obtained by imaging techniques and the cross-sectional areas obtained by AR, with particularly high agreement in the anterior nasal cavity. However, with the exception of studies by Terheyden et al. and Cakmak et al. in all previous investigations of living subjects the CT and magnetic resonance images were taken perpendicular to the floor of the nose. Moreover, some investigations used the distances from the anterior nasal spine, whereas others used the tip of the nose as the reference point. Clearly, it is difficult to make definitive statements about the validity of AR on the basis of data from different imaging techniques, different imaging axes, and potentially different sites in the nasal passage due to different reference points.

Similar to studies in which imaging methods have been used in healthy human subjects, model studies have shown that AR is valuable for measuring nasal valve passage area if this area is within the normal adult range. However, pipe model studies have shown that certain factors inherent to the physics and algorithms used in AR limit the accuracy of this method and lead to systematic measurement errors. These studies suggest that the accuracy of AR measurements diminished at locations beyond a significant constriction at the nasal valve, and also at regions posterior to a paranasal sinus ostium, depending on the ostium size and/or the sinus volume. When the passage area of the nasal valve was small, AR-derived cross-sectional areas beyond the constriction were consistently underestimated and the corresponding area-distance curves showed pronounced oscillations. Previous model studies also demonstrated that paranasal sinuses led to area overestimation and oscillation of the AR curve posterior to the sinus ostium when the ostium was relatively large. Area underestimation or overestimation, as well as oscillations of the AR curve (the physical reasons for which have been discussed), may easily lead to misinterpretation of a patient's nasal anatomy or condition. To avoid such misinterpretations, AR should be performed in combination with other methods such as anterior rhinoscopy and endoscopy.

Acoustic rhinometry has been widely used in clinical trials, but very little is known about how changes in the anatomy of the nasal cavity affect the accuracy of AR measurements. Several authors have investigated the sensitivity of AR in realistic nose models and in the living human nasal cavity by placing inserts at various sites in the nasal passage. Hilberg et al. placed 0.3 cm spheres at different locations in a cast model and found that AR was able to positively interpret the presence or absence of these objects. Similarly, Lenders et al. inserted small pieces of wax (volumes, 0.1 to 0.6 cm$^3$) at different locations in cast models. They found that a wax piece 0.3 cm$^3$ in volume placed in the middle meatus was detected by AR, but observed no changes in the AR curve when the same insert was placed in the posterior nasal cavity. Fisher et al. placed 0.3, 0.5, and 0.7 cm diameter spheres into either the middle meatus or the nasal valve of living subjects to assess how well AR would detect these objects. The smallest spheres (0.3 cm diameter) were detected in only a minority of cases, those 0.5 cm in diameter were detected in most cases, and those 0.7 cm in diameter were identified in the large majority of cases. Although detection rates were similar for both locations, the authors observed greater changes in area and volume for the 0.3 and 0.5 cm spheres placed in the middle meatus than for those placed in the nasal valve. However, in the present study we observed the opposite: AR was more sensitive in detecting different-sized spherical inserts in the nasal valve than in detecting them at all locations posterior to the nasal valve.

CONCLUSIONS

The results of the present study show that when the passage area of the nasal valve is within the normal adult range, AR measures cross-sectional areas in the anterior nasal cavity with high precision, whereas cross-sectional areas at posterior locations are
overestimated. The first minimum on the AR area-distance curve represents the junction between the end of the nosepiece and the nostril, and the second one corresponds to the nasal valve. Acoustic rhinometry accurately measures both the passage area and the location of the nasal valve. The nasal valve and choana are identified by pronounced dips on the AR curve, whereas the head of the inferior turbinate, the head of the middle turbinate, the middle of the middle turbinate, and the nasopharynx are not distinguishable on the curve. The reasons for this lack are the limited spatial resolution of AR and the inability of AR to reproduce sharp changes in cross-sectional area throughout the course of the nasal passage. The results also show that AR is sensitive in detecting changes in passage area at the nasal valve, but that its sensitivity is much lower at posterior sites. When the nasal valve region is significantly narrowed, AR does not detect obstructions at sites beyond this region.

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