Acoustic Rhinometry in Healthy Humans: Accuracy of Area Estimates and Ability to Quantify Certain Anatomic Structures in the Nasal Cavity

Mehmet Cankurtaran, PhD; Huseyin Çelik, PhD; Mehmet Coşkun, MD; Evren Hizal, MD; Ozcan Cakmak, MD

Objectives: We evaluated the accuracy of acoustic rhinometry (AR) measurements in healthy humans and assessed the ability of AR in quantifying the dimensions of the paranasal sinuses and certain anatomic structures in the nasal cavity.

Methods: Twenty nasal passages of 10 healthy adults were examined by AR and computed tomography (CT) before and after decongestion. Actual cross-sectional areas of the nasal cavity and actual locations of the nasal valve, the head of the inferior turbinate, the head of the middle turbinate, the ostia of the frontal and maxillary sinuses, and the choana were determined from CT sections perpendicular to the curved acoustic axis of the nasal passage.

Results: The AR-measured cross-sectional areas in the anterior nasal cavity were in reasonable agreement with the corresponding areas determined from CT, whereas AR consistently overestimated the passage areas at locations posterior to the paranasal sinus ostia. The nasal valve was identified as a pronounced minimum on the AR area-distance curve. However, AR did not discretely identify the head of the inferior turbinate, the head of the middle turbinate, or the choana.

Conclusions: The local minima on the AR area-distance curve beyond the nasal valve are caused by acoustic resonances in the nasal cavity, and do not correspond to any anatomic structure. The AR area overestimation beyond the paranasal sinus ostia is due to the interaction between the nasal cavity and the paranasal sinuses, rather than to sound loss into the sinuses. Acoustic rhinometry provides no quantitative information on ostium size or sinus volume in either non-decongested or decongested nasal cavities.

Key Words: acoustic rhinometry, computed tomography, nasal cavity, nasal valve, paranasal sinus, turbinate.

INTRODUCTION

Acoustic rhinometry (AR) was introduced by Hilberg et al\(^1\) as an objective method for examining the nasal cavity. This technique is based on the principle that a sound wave propagating in the nasal cavity is reflected by local changes in acoustic impedance. However, certain factors inherent to the physics and algorithms used in AR limit the accuracy of this method and lead to systematic measurement errors. Previous investigations of living human subjects have demonstrated reasonably good agreement between the cross-sectional areas in the anterior part of the nasal cavity determined by AR, and those determined by imaging techniques such as magnetic resonance imaging (MRI) and computed tomography (CT; for review, see Hilberg\(^2\) and Cakmak et al\(^3\)). However, in the posterior part of the nasal cavity and the nasopharynx, AR consistently overestimates cross-sectional areas compared to MRI and CT.

Inspection of the literature reveals that up to 4 local minima have been commonly observed on the AR area-distance curves for living humans. The main results of earlier AR studies of healthy (normal) humans can be summarized as follows.\(^2,4\)

1. In a non-decongested nasal cavity, the first 2 local minima on the AR area-distance curve were located approximately 3 cm from the nostril; the first minimum was attributed to the nasal valve, the second to the head of the inferior turbinate (concha). The third minimum was usually attributed to the head of the middle turbinate.

2. After decongestion of the nose, both the first and second minima moved anteriorly; however, the forward displacement of the minimum corresponding to the head of the inferior turbinate was more pronounced than the forward displacement of the minimum corresponding to the nasal valve.
3. The area overestimation with AR in the posterior part of the nasal cavity was mainly attributed to sound loss to the paranasal sinuses (especially the maxillary sinus). It was also hypothesized that information about the paranasal sinuses and sinus ostia might be found in the portion of the AR area-distance curve between 5 and 10 cm.

However, almost all AR results summarized above were accumulated about 10 to 15 years ago; they were based solely on clinical observations, and they have not been validated by CT or MRI measurements. Nonetheless, all of these AR findings have been uncritically accepted and were included in the most recent “Consensus Report on Acoustic Rhinometry and Rhinomanometry.” However, even for healthy humans, there is no clear consensus on the interpretation of these AR results. Moreover, the contributors to this consensus report did not consider the results of recent experimental and theoretical studies of the effects of the nasal valve and the paranasal sinuses on the AR area-distance curves for models simulating the nasal cavity.

The aims of this investigation were to evaluate the accuracy of AR for assessing the nasal cavity in healthy humans before and after decongestion, and to evaluate the ability of AR in quantifying the paranasal sinuses and anatomic structures at specific sites in the nose. These sites corresponded to the nasal valve, the head of the inferior turbinate, the head of the middle turbinate, the openings of the ostia of the frontal and maxillary sinuses, and the choana. The actual cross-sectional areas of the nasal cavity were calculated from CT sections perpendicular to the curved acoustic axis of the nasal passage and were then compared with the corresponding cross-sectional areas measured by AR. The actual location of each of these anatomic sites and its distance from the nostril (along the curved acoustic axis), the effective diameters of the ostia of the frontal and maxillary sinuses, and the volume of the maxillary sinus were determined by CT.

MATERIALS AND METHODS

The Institutional Review Board of Baskent University approved the study protocol. Twenty nasal passages of 10 healthy adult volunteers were examined by CT and AR. Subjects with a history of allergy, nasal surgery, or medication and those who had a nasal and/or paranasal sinus infection or a major structural nasal disorder such as septal deviation or turbinate hypertrophy were excluded from the study. All AR and CT examinations were performed before and 10 to 15 minutes after decongestion with 3 sprays per nostril of 0.05% xylometazoline hydrochloride nasal spray. The AR and CT examinations of a selected subject were performed on the same day.

A transient-signal acoustic rhinometer (EccoVision, Hood Instruments, Pembroke, Massachusetts) was used to perform the acoustic measurements. For each nasal cavity, a properly fitted nosepiece was selected and a thin layer of ointment was applied to prevent any acoustic leakage from the junction between the nosepiece and the nostril. Special care was taken not to obstruct the nasal vestibule with ointment or distort the nasal valve anatomy, and to position the nosepiece such that it was only in light contact with the nostril during the assessment. All AR measurements were repeated at least 5 times to ensure that the results were reproducible.

Computed tomography examinations of the nasal cavity 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 scans parallel to the floor of the nose 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 bone algorithm. To determine the actual cross-sectional areas of the nasal cavity, we divided the curved acoustic pathway of the human nasal passage into 3 parts, and drew each manually on a separate CT image (Fig 1). The first part of the curved acoustic axis was drawn as a quarter circle that started from the center of the nostril and extended to the anterior wall of the frontal sinus. The second part was drawn as a straight line running parallel to the hard palate from the end point of the first portion of the acoustic axis to the choana. The third part was drawn as a quarter circle that followed the

Fig 1. Sagittal computed tomography (CT) image of nasal cavity of one healthy human subject in study. Dashed line represents presumed acoustic axis, that follows curved shape of nasal passage and nasopharynx.
The actual mean locations of the nasal valve, the head of the middle turbinate, the openings of the ostia of the frontal and maxillary sinuses, and the choana were not affected by decongestion (Table 1). However, the head of the inferior turbinate moved 0.18 cm posteriorly with decongestion. Decongestion of the nasal cavity caused no measurable influence on the size of the openings of the ostia of the frontal (mean ± SD, 0.105 ± 0.022 cm before and 0.118 ± 0.027 cm after) and maxillary (0.091 ± 0.029 cm before and 0.094 ± 0.030 cm after) sinuses.

Typical examples of the area-distance curves obtained from CT and AR examinations of the nasal cavities investigated in this study are shown in Figs 2 and 3. In all CT area-distance curves obtained before and after decongestion, the nasal valve was
characterized by a marked minimum. However, in the majority of decongested nasal cavities, the head of the inferior turbinate and the head of the middle turbinate did not cause any measurable changes at the corresponding locations on the CT area-distance curves. A small decrease (0.12 cm$^2$) in the cross-sectional area of the nasal passage was measured at the site of the head of the inferior turbinate in 2 decongested nasal cavities (Fig 2A). A similar reduction (0.14 cm$^2$) in cross-sectional area was observed at the site of the head of the middle turbinate in only 1 decongested nasal cavity (Fig 3A).

The CT area-distance curves for 13 non-decongested nasal cavities showed no measurable change at the location corresponding to the head of the inferior turbinate. For the head of the middle turbinate, the same held true for 9 non-decongested nasal cavities. In the remaining 7 non-decongested nasal cavities, the CT area-distance curves showed a decrease (ranging from 0.1 to 0.4 cm$^2$) in cross-sectional area was observed at the head of the middle turbinate in 4 non-decongested nasal cavities (Fig 2A). A small decrease (less than 0.25 cm$^2$) in cross-sectional area was observed at the head of the middle turbinate in 4 non-decongested nasal cavities. In summary, neither of these 2 anatomic sites could be distinctly identified on the CT area-distance curves for non-decongested and decongested nasal cavities. Regarding the locations of the openings of the ostia of the frontal and maxillary sinuses, the same conclusion was drawn from careful inspection of the CT area-distance curves for all nasal cavities examined before and after decongestion (Figs 2A and 3A). The right and left nasal passages of the human nose merge at the epipharynx. Therefore, the CT-determined cross-sectional areas at distances posterior to the choana represent the cross-sectional areas of the larger space formed by the union of the 2 passages at this location. The section of the CT area-distance curves corresponding to the portion of the nasal cavity from the maxillary sinus ostium to the choana exhibited small but measurable fluctuations, which might have been caused by ethmoid cells located in this portion of the nasal airway.

One feature common to all of the nasal passageways was oscillation of AR-measured cross-sectional areas, which was more pronounced for decongested nasal cavities (Figs 2B and 3B). Three or 4 local minima (and maxima in between) characterized the first 12 cm of the AR area-distance curves. The AR area-distance curves obtained for decongested and non-decongested nasal cavities started to deviate from each other at (or immediately beyond) the first minimum. Then the 2 curves rose progressively and oscillated as a function of distance. These AR results indicate that the effects of decongestion extended far beyond the choana and into the nasopharynx, which is unlikely.

The distances from the nostril to each of the local minima on the AR area-distance curves are collated in Table 2. The first minimum moved anteriorly from 1.94 ± 0.21 cm to 1.82 ± 0.21 cm with decongestion. In contrast to the results of a number of earlier AR studies of healthy human subjects, the second minimum shifted posteriorly from 3.80 ± 0.51 cm to 4.16 ± 0.71 cm with decongestion. The third and the fourth minima on the AR curve also moved posteriorly with decongestion from 5.57 ± 0.81 cm
to 6.78 ± 1.06 cm and from 9.74 ± 1.18 cm to 10.1 ± 1.20 cm, respectively.

Comparison of CT-determined mean distances to the nasal valve, the head of the inferior turbinate, and the head of the middle turbinate from the nostril (Table 1) with AR-determined mean distances of the first, second, and third minima from the nostril (Table 2) revealed the following:

1. The first minimum on the AR area-distance curve corresponds to the nasal valve. However, AR overestimated its mean location by 0.27 cm and 0.17 cm for non-decongested and decongested nasal cavities, respectively.

2. The mean location of the second minimum on the AR area-distance curve was 0.61 cm and 0.79 cm beyond the actual mean location of the head of the inferior turbinate, respectively, before and after decongestion. This result indicates that the second minimum on the AR area-distance curve cannot be attributed to the head of the inferior turbinate. In decongested nasal cavities, however, the mean distance of the second minimum from the nostril was approximately equal to the actual mean distance from the nostril to the head of the middle turbinate.

3. The mean distance from the nostril to the third minimum on the AR area-distance curve was considerably longer than the actual mean distances to the head of the middle turbinate and the openings of the ostia of the frontal and maxillary sinuses. This finding suggests that the third minimum on the AR curve does not represent any of these anatomic structures in either non-decongested or decongested nasal cavities.

4. The mean location of the fourth minimum on the AR area-distance curves was 1.0 cm and 1.3 cm posterior to the actual mean location of the choana determined from CT examinations of the nasal cavity before and after decongestion, respectively.

Nevertheless, comparison of only the locations of the minima on the AR area-distance curve with the CT-determined actual locations of certain anatomic structures in the nasal cavity does not provide a complete description of the evaluation procedure of AR. It is also necessary to compare the CT-measured cross-sectional areas of the nasal passage at certain anatomic sites with the cross-sectional areas estimated by AR at the corresponding locations.

The actual cross-sectional areas determined from CT for both non-decongested and decongested nasal cavities were in reasonable agreement with the corresponding cross-sectional areas obtained from AR.
up to the immediate vicinity of the maxillary sinus ostium (Fig 4). In the region from the maxillary sinus ostium to the choana, AR consistently overestimated the cross-sectional areas for all nasal cavities examined in this study. The degree of AR area overestimation increased as the distance beyond the maxillary sinus ostium increased, and was extremely high at the location of the choana.

In most of the 20 nasal cavities examined before and after decongestion, AR greatly overestimated the cross-sectional areas of the nasal airway beyond the choana (Fig 4B). However, in some nasal cavities, the CT- and AR-derived cross-sectional areas at distances approximately 1.0 cm beyond the choana were fairly closely aligned (Fig 4A). In other words, AR did not provide reliable quantitative data for the cross-sectional area of the nasopharynx.

The mean passage areas of the nasal valve measured with CT before and after decongestion were essentially the same, demonstrating that the mucosa of the nasal valve was not affected by decongestion (Table 3). However, the AR-measured mean cross-sectional area of the nasal valve increased considerably (19%) with decongestion. Furthermore, AR considerably underestimated the passage area of the nasal valve. The AR-measured mean passage areas of the nasal valve before and after decongestion were 37% and 26% smaller, respectively, than the corresponding CT results. Table 3 demonstrates also that for both non-decongested and decongested nasal cavities, CT and AR provided comparable results (within approximately 10%) for the mean cross-sectional areas of the nasal passage at the head of the inferior turbinate and the head of the middle turbinate.

To further evaluate the effects of decongestion on the nasal valve, we performed a linear regression analysis by taking the nasal valve passage area of non-decongested nasal cavities as the independent variable and that of decongested nasal cavities as the dependent variable. The relevant statistical data are given in Fig 5 (intercept [A] and slope [B] of the best-fit straight line through the experimental data points determined by the least-squares method, linear correlation coefficient [R^2], and p value). If the passage areas of the nasal valve determined by either CT or AR for non-decongested and decongested nasal cavities were identical, then the intercept would be zero and the slope would be unity. Indeed, for CT results (Fig 5A), the intercept (A = 0.06 cm^2) was extremely small and the slope (B = 0.95) was very close to unity. Figure 5A demonstrates also a very high, statistically significant correlation (R^2 = 0.94; p < .0001) between the CT-measured passage areas of the nasal valve for non-decongested and de-congested nasal cavities.

<table>
<thead>
<tr>
<th>Anatomic Site</th>
<th>Before Decongestion</th>
<th>After Decongestion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT (cm^2; mean ± SD)</td>
<td>AR (cm^2; mean ± SD)</td>
</tr>
<tr>
<td>Nasal valve</td>
<td>0.76 ± 0.18</td>
<td>0.48 ± 0.16</td>
</tr>
<tr>
<td>Head of inferior turbinate</td>
<td>1.04 ± 0.45</td>
<td>0.92 ± 0.32</td>
</tr>
<tr>
<td>Head of middle turbinate</td>
<td>1.21 ± 0.67</td>
<td>1.18 ± 0.40</td>
</tr>
</tbody>
</table>
congested nasal cavities. Similarly, Fig 5B shows a statistically significant correlation \( R^2 = 0.68; p < .0001 \) between the AR-measured passage areas of the nasal valve in non-decongested and decongested nasal cavities. Nevertheless, the much larger intercept \( A = 0.31 \text{ cm}^2 \) and the much smaller slope \( B = 0.53 \) of the best-fit line further indicated that the AR-measured passage area of the nasal valve was consistently larger in decongested than in non-decongested nasal cavities.

Next, to further evaluate the correlation between CT and AR measurements of the anterior nasal cavity, we performed linear regression analysis between the cross-sectional areas determined from CT and AR at the locations of the nasal valve, the head of the inferior turbinate, and the head of the middle turbinate (Table 4). Before decongestion, the correlation between the CT and AR results at the nasal valve was weak \( (p = .060) \); however, there was a statistically significant correlation between the cross-sectional areas determined by the 2 methods at the head of the inferior turbinate \( (p = .002) \) and the head of the middle turbinate \( (p = .003) \). After decongestion, there was a good, statistically significant correlation between the cross-sectional areas measured by the 2 methods at each of these 3 anatomic sites. The correlation between the CT and AR results was better in decongested than in non-decongested nasal cavities, as indicated by the much higher values of \( R^2 \) and the much smaller \( p \) values (Table 4).

Finally, to ascertain whether AR provides quantitative information about the size of the paranasal sinus ostia and sinus cavity volume, we calculated the CT volume and AR volume for each of the 20 nasal passages examined before and after decongestion. The CT and AR volumes were calculated by integrating the areas under the CT- and AR-derived area-distance curves, respectively, over the distance from the nostril to the choana. Acoustic rhinometry overestimated the mean volume of the nasal airway by 21% and 24% for non-decongested and decongested nasal cavities, respectively (Table 5). Decongestion of the nose is not expected to affect the paranasal sinus volume, because the mucosa covering the sinus cavity does not possess erectile tissue. To test this idea, we determined the maxillary sinus volumes for each of 3 randomly selected nasal cavities (Nos. 4, 8, and 10) on CT, which were 20.4, 11.4, and 19.9 cm³ before decongestion and 20.3, 11.8, and 20.1 cm³ after decongestion. These results show that decongestion had no effect on maxillary sinus volume. If AR area overestimation beyond the sinus ostia were due to loss of sound into the paranasal sinus cavities, the difference between AR vol-

### Table 4. Statistical Data Obtained from Linear Regression Analysis Between CT-Determined Cross-Sectional Area (Independent Variable) and AR-Determined Cross-Sectional Area (Dependent Variable)

<table>
<thead>
<tr>
<th>Anatomic Site</th>
<th>Before Decongestion</th>
<th>After Decongestion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( A (\text{cm}^2) )</td>
<td>( B )</td>
</tr>
<tr>
<td>Nasal valve</td>
<td>0.20</td>
<td>0.38</td>
</tr>
<tr>
<td>Head of inferior turbinate</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Head of middle turbinate</td>
<td>0.73</td>
<td>0.38</td>
</tr>
</tbody>
</table>

\( A \) — intercept of best-fit straight line; \( B \) — slope of best-fit straight line; \( R^2 \) — linear correlation coefficient.
TABLE 5. MEAN VOLUME OF NASAL CAVITY FROM NOSTRIL TO CHOANA AS DETERMINED FROM CT AND AR MEASUREMENTS OF 20 NASAL CAVITIES

<table>
<thead>
<tr>
<th></th>
<th>Before Decongestion</th>
<th>After Decongestion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT</td>
<td>AR</td>
</tr>
<tr>
<td>Mean volume (cm³)</td>
<td>10.3</td>
<td>12.5</td>
</tr>
<tr>
<td>SD (cm³)</td>
<td>2.9</td>
<td>3.5</td>
</tr>
<tr>
<td>Range (cm³)</td>
<td>5.9-17.0</td>
<td>6.3-21.6</td>
</tr>
<tr>
<td>Percentage difference, 100(AR – CT)/CT</td>
<td>21</td>
<td>24</td>
</tr>
</tbody>
</table>

...and CT volume would be comparable to the total volume of the paranasal sinuses for each nasal passage.9 However, the difference between the mean values of AR- and CT-determined volumes (Table 5) was much smaller than the volume of the maxillary sinus alone. The results indicate that for both non-decongested and decongested nasal cavities examined in this study, the AR area overestimation beyond the paranasal sinus ostia cannot be attributed to sound loss through the sinus ostia into the paranasal sinuses.

The data presented in Table 5 also provide a quantitative measure of the effects of decongestion on the nasal mucosa. The difference (7.5 cm³) between the AR-determined mean volumes of decongested and non-decongested nasal cavities was 30% larger than the difference (5.8 cm³) between the corresponding CT-determined mean volumes, which can be taken as the actual change in the volume of nasal mucosa during decongestion. The results indicate that AR considerably overestimated the effects of decongestion on the volume of the erectile tissue in the nasal cavity. Linear regression analysis revealed a statistically significant correlation (R² = 0.59; p = .006) between the CT-measured volumes of non-decongested and decongested nasal cavities; however, there was no correlation (R² = 0.27; p = .242) between the corresponding AR-measured volumes. In all, the results suggest that AR did not provide reliable quantitative information on the nasal cavity volume (from nostril to choana) or, hence, on the effects of decongestion on the nasal mucosa.

DISCUSSION

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 size and locations on this curve. However, 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. Our present study demonstrated that only the nasal valve was identified as a pronounced minimum on the actual area-distance curves determined by CT for each of the 20 nasal cavities examined before and after decongestion. Decongestion had no measurable effect on the actual mean location of the nasal valve. The first minimum on the AR area-distance curve corresponded to the nasal valve. However, AR overestimated the mean location of the nasal valve for both non-decongested and decongested nasal cavities, as compared to the corresponding CT results. The AR-determined mean location of the nasal valve moved 0.10 cm anteriorly with decongestion; however, this anterior displacement is much smaller than the spatial resolution of the AR technique.9,10

The CT measurements showed that the mean area and the mucosa of the nasal valve were not affected by decongestion. In contrast, the AR-measured mean area at the nasal valve increased substantially with decongestion. A number of earlier studies have interpreted this AR result as if there were erectile tissue at the nasal valve area.12-14

In contrast to the nasal valve, neither the head of the inferior turbinate nor the head of the middle turbinate could be distinctly identified on the CT area-distance curves of healthy humans. The same held true for the AR results. The second and third minima on the AR area-distance curves for both non-decongested and decongested nasal cavities did not correspond to the actual locations of the head of the inferior turbinate and the head of the middle turbinate determined from CT.

Some previous AR studies have suggested that the second minimum on the AR area-distance curve corresponds to the head of the inferior turbinate, and shifts anteriorly with decongestion (for review, see Hilberg2). This is in striking contrast to the results of our present CT study, which demonstrated that the actual mean location of the head of the inferior turbinate shifted posteriorly with decongestion. However, this posterior displacement (0.18 cm) was too small to be resolved by AR. As the nasal mucosa undergoes decongestion, the most anterior part of the inferior turbinate retracts with respect to its location in the non-decongested nasal cavity.14,15 Therefore, if the second minimum on the AR area-distance curve were attributable to the head of the inferior turbinate, one would expect it to move posteriorly with decongestion, not anteriorly. The present study showed that the mean location of the second minimum on the AR curve moved 0.36 cm posteriorly with decongestion, a finding that contradicts the results of previous AR studies.

For the decongested nasal cavities examined in
this study, the CT-determined mean distance of the head of the middle turbinate from the nostril was similar to that of the second minimum on the AR area-distance curves. However, this correspondence should be treated as fortuitous, because the CT area-distance curves of the majority of decongested nasal cavities did not feature a distinct minimum at the head of the middle turbinate. In a study that used cast models of the nasal cavity, Cakmak et al\textsuperscript{16} demonstrated that AR was able to detect changes in cross-sectional area larger than approximately 0.19 cm\textsuperscript{2} and 0.38 cm\textsuperscript{2} at the head of the inferior turbinate and the head of the middle turbinate, respectively. This finding suggests that any change in the cross-sectional area of the nasal passage at each of these specific anatomic sites that is smaller than the corresponding limit cannot be resolved by AR. In addition, the ability of AR in measuring abrupt changes in cross-sectional area is poor, because of the limited spatial resolution and the long rise distance of the technique.\textsuperscript{6,10,11} In summary, with the exception of the first minimum, which represents the nasal valve, the subsequent minima on the AR area-distance curves for both non-decongested and decongested nasal cavities do not correspond to any anatomic structure in the healthy human nose.

The present study showed that both the oscillating pattern of the AR area-distance curve and the area overestimation beyond the paranasal sinuses ostia were common to all 20 nasal passages examined before and after decongestion. This result suggests that these two AR phenomena are inherent to the physics of sound wave transmission through the nasal cavity. The sound waves propagating in the nasal cavity undergo partial reflections and transmissions at all locations in which the acoustic impedance changes. Hence, superposition of the sound waves traveling in opposite directions within the nasal cavity generates a complicated pattern of standing waves.\textsuperscript{5} Taking into account the CT-determined actual size (effective diameter and length) of the portion of the nasal cavity from the nasal valve to the choana, we estimated the fundamental resonant frequency of the nasal cavity to be approximately 2,260 Hz before decongestion and approximately 2,240 Hz after decongestion. Thus, the fundamental frequency and the first 3 overtones of the nasal cavity fall within the frequency bandwidth of the acoustic rhinometer. Therefore, the oscillation of the AR area-distance curve (ie, the minima and maxima beyond the nasal valve) is due to these acoustic resonances in the nasal cavity. Cankurtaran et al\textsuperscript{5} theoretically proved that the oscillating pattern of the AR area-distance curves of pipe models simulating the nasal cavity is caused by acoustic resonances in the model. They demonstrated that for a plane sound wave of wavelength $\lambda$, the distance between 2 consecutive minima (or maxima) in a pipe of finite length is equal to $\lambda/2$.

For the majority of non-decongested and decongested nasal cavities examined in the present study, the portion of AR area-distance curves beyond the nasal valve featured local minima (or maxima) at every 11 to 12 data points. The AR instrument produces a data point every 0.24 cm, implying that $\lambda/2$ is approximately equal to 2.9 cm, corresponding to a frequency of approximately 5,910 Hz, which falls between the first and second overtones mentioned above. According to Table 2, for decongested nasal cavities, the average distance between the second and third minima and that between the third and fourth minima on the AR area-distance curves were approximately 2.7 cm and 3.2 cm, respectively. For non-decongested nasal cavities, the corresponding average distances were approximately 2.0 cm and 3.5 cm. This finding further supports the suggestion that the oscillation of the AR area-distance curve in the portion of the nasal cavity beyond the nasal valve is due to acoustic resonances in this region. However, because of differences between the actual size and geometry of individual nasal cavities and complicated phase relationships between the acoustic resonances of different frequencies, the portion of the AR curve beyond the nasal valve featured 2 minima in some subjects and 3 minima in others. The AR-measured locations of these minima are expected to vary somewhat with decongestion because of the changes in the size of the nasal cavity, as observed experimentally. In summary, AR only discretely identifies the nasal valve, whereas the minima and the maxima on the AR area-distance curve at locations beyond the nasal valve are caused by the acoustic resonances in the nasal cavity. It appears that the minima usually observed with AR beyond the nasal valve have been misinterpreted in previous clinical studies as though they corresponded to certain anatomic structures in the nasal cavity.\textsuperscript{12,17-21}

Some previous studies have suggested that sound loss through the sinuses ostia into the paranasal sinuses would lead to AR overestimation of the cross-sectional areas of the nasal cavity posterior to these openings.\textsuperscript{8,22-24} Hilberg noted, “It may be possible to compensate for these losses and probably also get valuable information of the function of the sinuses ostia.”\textsuperscript{20,24} However, until recently, interpretation and discussions of the effects of the paranasal sinuses on AR results had been qualitative, and based solely on experimental data. No attempts had been made to theoretically investigate the effects of the paranasal sinuses on the AR area-distance curve.
Previously, Cakmak et al\textsuperscript{7} published an experimental and theoretical study that involved the use of pipe models with a Helmholtz resonator as a side branch, simulating a paranasal sinus. For models in which the passage area of the simulated nasal valve was in the normal adult range, they found that AR consistently overestimated cross-sectional areas posterior to the ostium, and that the AR area-distance curves showed oscillations. Cakmak et al\textsuperscript{7} argued that AR area overestimation is not due to loss of sound energy into the side branch. They concluded that the algorithms used in AR do not account for the effects of the asymmetric branching represented by paranasal sinuses connected to the nasal cavity via sinus ostia. A more recent study\textsuperscript{25} that used cast models of the nasal cavity showed that regardless of the particular shape of the model, AR overestimated cross-sectional areas beyond the simulated sinus ostium (see also Mlynski et al\textsuperscript{26}).

Tarhan et al\textsuperscript{9} published a comprehensive study that involved 10 healthy human subjects examined by CT and AR after decongestion. Their results demonstrated that AR consistently overestimated cross-sectional areas in the portion of the nasal cavity beyond the paranasal sinus ostia, and that the effect did not correlate with the size of the sinus ostia or the volumes of the frontal and maxillary sinuses. Tarhan et al\textsuperscript{9} also showed that the fundamental resonant frequencies of the frontal and maxillary sinuses were within the frequency bandwidth of the AR instrument used in the study. Their results confirmed the previous theoretical predictions\textsuperscript{7} that AR area overestimation is due to interaction between the nasal cavity and the paranasal sinuses, and not to loss of sound energy into the sinuses via the ostia. The oscillations set up by the resonant behavior of the paranasal sinuses are superimposed on the signal reflected from more posterior parts of the nasal cavity, which is then incorrectly interpreted by the AR algorithms as area overestimation.

Our present study shows that the actual size of the ostia of the frontal and maxillary sinuses and the maxillary sinus volume are not affected by decongestion. Therefore, the above argument should also be valid for non-decongested nasal cavities. The opening to a paranasal sinus causes a significant change in the acoustic impedance of the nasal passage at that site; however, the average sound energy loss to the sinus is negligible. The results of our present and previous\textsuperscript{9} clinical studies of healthy humans and previous model studies\textsuperscript{5-7,25} reveal that the complex acoustic impedances of the nasal cavity and paranasal sinuses (and, hence, the effects of acoustic resonances in the nasal cavity and sinuses) are not accounted for in the current AR algorithms. Consequently, AR does not provide quantitative information about paranasal sinus volume or ostium size in either non-decongested or decongested nasal cavities, and it considerably overestimates cross-sectional areas in the nasal passage beyond the paranasal sinus ostia.

CONCLUSIONS

The results of the present study of healthy humans show that AR measures cross-sectional areas in the anterior nasal cavity with reasonably high accuracy, whereas cross-sectional areas at locations posterior to the paranasal sinus ostia are greatly overestimated in AR measurements. The nasal valve is identified by a pronounced minimum (the first minimum after the nostril) on the AR area-distance curve. Acoustic rhinometry slightly overestimates the location of the nasal valve, but considerably underestimates its passage area in both non-decongested and decongested nasal cavities, as compared to CT results. However, the second, third, and fourth local minima on the AR area-distance curve do not correspond to any anatomic structure in the nasal passage. These 3 minima are caused by acoustic resonances in the portion of the nasal cavity beyond the nasal valve. The area overestimation beyond the paranasal sinus ostia is due to the interaction between the nasal cavity and the paranasal sinuses, and not to sound loss through the ostia into the sinuses. Acoustic rhinometry fails to provide quantitative information about paranasal sinus volume and ostium size in both non-decongested and decongested nasal cavities. Acoustic rhinometry considerably overestimates the effects of decongestion on the volume of the nasal mucosa.

REFERENCES


