Acoustic rhinometry in humans: accuracy of nasal passage area estimates, and ability to quantify paranasal sinus volume and ostium size

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Tarhan, Erkan, Mehmet Coskun, Ozcan Cakmak, Hüseyin Çelik, and Mehmet Cankurtaran. Acoustic rhinometry in humans: accuracy of nasal passage area estimates, and ability to quantify paranasal sinus volume and ostium size. J Appl Physiol 99: 616–623, 2005. First published March 31, 2005; doi:10.1152/japplphysiol.00106.2005.—A comprehensive study that compared acoustic rhinometry (AR) data to computed tomography (CT) data was performed to evaluate the accuracy of AR measurements in estimating nasal passage area and to assess its ability of quantifying paranasal sinus volume and ostium size in live humans. Twenty nasal passages of 10 healthy adults were examined by using AR and CT. Actual cross-sectional areas of the nasal cavity, sinus ostia sizes, and maxillary and frontal sinus volumes were determined from CT sections perpendicular to the curved acoustic axis of the nasal passage. Nasal cavity volume (from nostril to choana) calculated from the AR-derived area-distance curve was compared with that from the CT-derived area-distance curve. AR measurements were also done on pipe models that featured a side branch (Helmholtz resonator of constant volume but two different neck diameters) simulating a paranasal sinus. In the anterior nasal cavity, there was good agreement between the cross-sectional areas determined by AR and CT. However, posterior to the sinus ostia, AR overestimated cross-sectional area. The difference between AR nasal volume and CT nasal volume was much smaller than the combined volume of the maxillary and frontal sinuses. The results suggest that AR measurements of the healthy adult nasal cavity are reasonably accurate to the level of the paranasal sinus ostia. Beyond this point, AR overestimates cross-sectional area and provides no quantitative data for sinus volume or ostium size. The effects of paranasal sinuses and acoustic resonances in the nasal cavity are not accounted for in the present AR algorithms.

Previous studies have suggested that sound loss through the sinus ostia into the paranasal sinuses would lead to AR overestimation of the cross-sectional areas of the nasal cavity posterior to these openings (7, 8, 14, 18, 19, 25, 26). However, none has provided a satisfactory theoretical explanation of this phenomenon. A recent study by Cakmak et al. (1) examined the effects of paranasal sinuses on AR measurements using pipe models that had a Helmholtz resonator attached as a side branch to simulate the paranasal sinuses. 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 degree of error depended on ostium size and/or paranasal sinus volume. The authors argued that the area overestimation was not due to sound loss through the ostia into the paranasal sinuses. A more recent study that involved cast models of the nasal cavity revealed that, regardless of the particular shape of the model, AR overestimated cross-sectional areas beyond the simulated sinus ostium (2). However, the nasal cavity models used in these previous studies do not reflect the acoustic properties of the actual nasal cavity lined with mucosa.

Cakmak and coworkers (3) conducted a clinical study of 25 healthy adults that focused on the nasal valve region in particular. The results showed that AR is a valuable method for measuring the passage area of the nasal valve. The authors found a significant correlation between the passage areas of the nasal valve determined by AR and CT, when CT imaging was done perpendicular to the curved acoustic axis (11, 14). We planned the present study as a continuation of this previous work (3), evaluating AR for the entire nasal cavity rather than one zone only.

The aims of this investigation were to evaluate the accuracy of AR for assessing nasal cavities in living human subjects, to learn the reasons for area overestimation in the posterior nasal cavity, and to assess the ability of AR in quantifying paranasal sinus volume and ostium size. The actual cross-sectional areas of the nasal cavity were calculated from CT sections perpendicular to the curved acoustic axis and were then compared with the corresponding cross-sectional areas measured by AR. Sizes of sinus ostia, distances from the ostia to the nostril, and volumes of the maxillary and frontal sinuses were determined by CT. To assess the effects that paranasal sinuses have on AR-derived area-distance curves, we also performed AR on pipe models that had a Helmholtz resonator attached as a side branch to simulate a paranasal sinus and ostium.

ACOUSTIC RHINOMETRY (AR) was introduced by Hilberg et al. (11) 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. AR is a simple, noninvasive technique, and as such it became widely accepted in a short period of time. Most 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 MRI and computed tomography (CT) (6, 10–12, 22, 24, 25). However, this does not hold true for the posterior part of the nasal cavity and the epipharynx, where AR significantly overestimates cross-sectional areas compared with MRI and CT.

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MATERIALS AND METHODS

In the clinical portion of this study, 20 nasal passages of 10 healthy adult volunteers were examined by CT and AR. Subjects with nasal-paranasal sinus infection, allergy, history of nasal surgery, or major structural nasal pathology (such as septal deviation or conchal hypertrophy), and those taking medication were excluded. The Institutional Review Board of Başkent University approved the study protocol (Project no. KA 04/09). All CT and AR examinations were performed 10–15 min after decongestion with three sprays per nostril of 0.05% xylometazoline hydrochloride nasal spray (Xylo-comod, Biem Ilç, Turkey).

Computed tomography. CT of the nasal cavity was performed by use of 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 scanning was done parallel to the floor of the nose by using 0.75-mm collimation, 2-mm slice thickness, and 5-mm table feet, and these images were reconstructed with 1-mm intervals at bone algorithm. To determine the actual cross-sectional areas of the nasal cavity, the acoustic pathway of the human nasal passage was divided into three parts, and each was manually drawn on a separate CT image (Fig. 1). The first part of the acoustic axis was drawn as a quarter circle that started from the center of the nostril and extended to the head of the inferior turbinate. 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 portion was drawn as a quarter circle that followed the pharyngeal curvature. The length of each of these three segments of the acoustic axis was measured on CT scan, and 30 cross sections perpendicular to the acoustic axis were obtained in each portion. The inner borders of the passageway were manually traced on each CT section to calculate cross-sectional areas (Fig. 2A). For each nasal passage, the cross-sectional area determined from CT was plotted vs. distance from the nostril to yield the “CT-derived area-distance curve.”

To assess how a paranasal sinus affects AR measurements, it is necessary to know the size (effective diameter and canal length) of the ostium and the volume of the sinus. For each subject, the sizes of the maxillary and frontal sinus ostia and the distances from each of these openings to the nostril were measured by CT (Table 1). We also used the CT images to determine the distance from the nostril to the location where the ethmoid cells (sinuses) opened into the nasal cavity. In each case, the volumes of the maxillary and frontal sinuses were calculated from CT as follows: first, the anterior-to-posterior lengths of these sinuses were measured from the axial CT scan of the nasal passages. Then, series of equally spaced CT cross sections perpendicular to the hard palate were obtained (10 slices for maxillary sinus measurements and 5 slices for frontal sinus measurements). Finally, the margin of the sinus cavity was manually traced on each CT section to derive the cross-sectional area (Fig. 2B). The volume of the sinus was taken as the sum of the products of cross-sectional area multiplied by distance between successive CT sections. Paranasal sinus volumes and ostium sizes varied greatly among the 10 subjects in the study (Table 2).

Acoustic rhinometry. A transient-signal acoustic rhinometer (Ecco Vision, Hood Instruments, Pembroke, MA) was used to perform the acoustic measurements. The processed bandwidth for this rhinometer ranged from 100 Hz to 10 kHz. A 10-kHz low-pass filter was used to reduce the errors associated with cross modes in the human nasal cavity. For each subject, a properly fitted nosepiece was selected and a thin layer of ointment was applied to prevent any acoustic leakage from the junction between the nostril and nosepiece. Special care was taken not to 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 five times to ensure the results were reproducible.

In addition to the clinical portion of the study, we also did testing with pipe models. As mentioned, paranasal sinuses can be mimicked experimentally by using an acoustic system commonly known as a Helmholtz resonator (20). These devices consist of a rigid cavity of volume V that communicates with the nasal cavity through a short neck/opening of diameter d and length l. The neck and the cavity of the Helmholtz resonator represent the sinus ostium and sinus volume,
Volumes of the subjects’ maxillary and frontal sinuses in the 20 nasal passages studied

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Maxillary Sinus Volume, cm³</th>
<th>Frontal Sinus Volume, cm³</th>
<th>Combined (Total) Sinus Volume, cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
<td>5</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
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<tr>
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<td>8</td>
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<tr>
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<td>4</td>
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</tr>
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<td>20</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
<td>10</td>
<td>31</td>
</tr>
</tbody>
</table>

All measurements were taken from computed tomography (CT).

respectively (1, 2). To achieve better understanding of how paranasal sinuses can influence AR results, and to determine the precise location at which AR-derived and CT-derived area-distance curves begin to deviate from each other, we created pipe models that simulated the nasal passage anatomy. Each model consisted of a brass pipe (12 cm long and 1.2 cm internal diameter) with a Helmholtz resonator as side branch. The neck and the cavity of the Helmholtz resonator represent the paranasal sinus ostium and the paranasal sinus volume (V), respectively. The neck diameter (d) was variable. A cylindrical insert with 0.60 cm² passage area (nasal valve simulator) was placed 2.0 cm from the left end of the pipe, which was connected to the nosepiece of the acoustic rhinometer.

RESULTS

Figure 4 shows typical examples of the area-distance curves that were obtained from CT and AR examinations of the human nasal cavities investigated. Both methods yielded comparable results for nasal valve passage area in each of the 20 nasal cavities studied (Table 3). The actual cross-sectional areas of the nasal cavity determined from CT were in good agreement with the corresponding cross-sectional areas determined from AR to a certain distance (L₀) from the nostril (Table 4). In the region from L₀ to the choana, AR significantly overestimated the cross-sectional areas for all 20 of the nasal passages examined in this study (Fig. 4). The AR-measured cross-sectional areas of the nasal passage anterior to the paranasal sinus ostium were unaffected by the presence of the paranasal sinuses. The ostia diameters ranged from 0.08 to 0.2 cm, and the maximum paranasal sinus volume was 22 cm³.

In Fig. 4, vertical arrows mark the actual CT-determined distances from the nostril to the openings of the maxillary and frontal sinuses (Table 1) and to the nasal valve and the choana. The distances from the nostril to the maxillary sinus ostia ranged from 4.4 to 5.8 cm, and the corresponding range for the distances to the frontal sinus ostia was 3.9 to 5.4 cm. Ethmoid cells (sinuses) were located at distances of 4.0–8.0 cm from the nostril. As Fig. 4 illustrates, in general, AR area overestimation started in the immediate vicinity of the frontal and maxillary sinus ostia, or ~1.0 cm beyond the maxillary sinus ostium. This location falls in the range of values found for L₀ (Table 4). In general, the degree of AR area overestimation rose as the distance beyond the sinus ostia increased and was extremely high (~85–165% of actual area) at the location of the choana. In summary, the data for the 20 nasal passages studied (all with nasal valve passage areas in the normal adult range; Table 3) revealed reasonably accurate AR measurements in the portion of the nasal cavity anterior to the paranasal

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sinus ostia. However, the accuracy of the measurements in the region posterior to the maxillary sinus ostium and the frontal recess was very low.

The right and left nasal passages of the human nose merge at the nasopharynx. Therefore, the CT-measured cross-sectional areas at distances posterior to the choana represent combined or “total” cross-sectional areas (Fig. 4). In other words, the large and abrupt rise in the CT-derived area-distance curve immediately posterior to the choana does not reflect massively increased area of a single (right or left) nasal passage, but rather the larger space formed by the union of the two passages at this location. In most of the 10 subjects who were examined in this study, AR greatly overestimated the total cross-sectional areas of the airway beyond the choana. However, in some cases, the CT- and AR-derived cross-sectional areas in the vicinity of the nasopharynx were fairly closely aligned. In all, AR did not provide reliable quantitative data for cross-sectional area of the nasopharynx.

One feature that was common to all the 20 nasal passages investigated was oscillation of AR-measured cross-sectional areas, and this was more pronounced at locations beyond the paranasal sinus ostia (Fig. 4). In particular, two local maxima (M1 and M2 in Fig. 4) characterized most of the AR-derived area-distance curves in this study. Although the amplitude of the oscillations varied somewhat from one nasal passage to another, the oscillation period (in units of length) was roughly constant.

Table 3. Subjects’ nasal valve passage areas as determined from CT and AR measurements

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>CT measurement</th>
<th>AR measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
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<td>0.73</td>
<td>0.90</td>
</tr>
<tr>
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<td>0.82</td>
</tr>
<tr>
<td>3</td>
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<tr>
<td>4</td>
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<td>0.79</td>
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<tr>
<td>6</td>
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<td>7</td>
<td>0.74</td>
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<td>0.84</td>
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<tr>
<td>9</td>
<td>0.81</td>
<td>0.60</td>
</tr>
<tr>
<td>10</td>
<td>0.70</td>
<td>0.68</td>
</tr>
</tbody>
</table>

AR, acoustic rhinometry.

Fig. 4. CT- and acoustic rhinometry (AR)-derived area-distance curves for 2 of the nasal passages in the study. The locations of the nasal valve (NV), the openings to the maxillary (MS) and frontal (FS) sinuses, and the choana (C) as determined from CT are marked with vertical arrows. M1 and M2 denote 2 local maxima on the AR area-distance curve (see text).

Fig. 5. AR-derived area-distance curves for 2 pipe models with a Helmholtz resonator of cavity volume $V = 12 \text{ cm}^3$ but different neck diameters $d$. The thick solid line represents the actual cross-sectional areas of the pipe with no side branch. The vertical arrow marks the location where the side branch was attached to the pipe.
curves show, the AR measurements anterior to the neck were almost identical. However, AR overestimated the cross-sectional area posterior to the neck. The degree of overestimation was linked with neck diameter, and this portion of both area-distance curves featured oscillations. Area overestimation started immediately at the site of branch attachment (the neck), and the degree of overestimation increased steadily beyond the neck. The curve for the model with resonator neck \( d = 0.15 \text{ cm} \) indicated much less area overestimation and smaller amplitude oscillation than the curve for the model with resonator neck \( d = 0.50 \text{ cm} \). The AR area-distance curves obtained for the pipe models were strikingly similar to those obtained for the nasal passages of the living subjects. Specifically, area overestimation beyond the sinus ostia (or simulated ostium) and oscillation of cross-sectional areas measured in this region of the passage (in particular, the maxima M1 and M2) are common to all the AR-derived area-distance curves presented in Figs. 4 and 5.

To further assess how paranasal sinuses affect AR results, we calculated the “AR volume” (VAR) and “CT volume” (VCT) for each of the 20 nasal passages by integrating the area under the AR- and CT-derived area-distance curves, respectively, for the distance from the nostril to the choana. The results obtained for VAR and VCT and the difference between these volume measures (\( \Delta V = V_{\text{AR}} - V_{\text{CT}} \)) are compiled in Table 5. For all the nasal passages examined, VAR was substantially larger than VCT. If AR area overestimation beyond the sinus ostia were due to loss of sound into the sinus cavities, \( \Delta V \) would be comparable to the total volume of the paranasal sinuses for each nasal passage. However, in almost all cases, the volume difference \( \Delta V \) was much smaller (~3–5 times smaller) than the volume of the maxillary sinus alone or the volume of the maxillary and frontal sinuses combined. One exception was subject 6. In this case, the combined maxillary + frontal sinus volume for each nasal passage was much smaller than the corresponding volumes for all other subjects. In summary, the data showed that the AR measurements provided no quantitative information about the volumes of the maxillary and frontal sinuses.

Figure 6 shows a plot of \( V_{\text{AR}} \) vs. \( V_{\text{CT}} \) (as calculated for the distance from the nostril to the choana) for the 20 nasal passages examined in this study. The straight line of best fit, as determined by the least squares method, was given by

\[
V_{\text{AR}} = a + mV_{\text{CT}}
\]

with intercept \( a = 9.5 \pm 2.1 \text{ cm}^3 \) and slope \( m = 0.67 \pm 0.14 \). The 95% confidence intervals of the intercept and slope were 5.1–13.9 and 0.38–0.95, respectively. If the nasal passage volumes determined by AR and CT were identical, then the intercept of the straight line would be zero and its slope would be unity. The \( a \) and \( m \) values for the line of best fit in Fig. 6 are further indication that AR consistently overestimates the cross-sectional area of the portion of the nasal cavity beyond the paranasal sinus ostia.

We performed a multiple linear regression analysis by taking the difference (\( \Delta V \)) between AR and CT volumes (Table 5) as dependent variable and the sinus volume, ostium diameter, and ostium canal length of maxillary and frontal sinuses (Tables 1 and 2) as independent variables. The analysis yielded \( P \) values of 0.914, 0.561, 0.904, 0.612, 0.783, and 0.139 for the six independent variables (the sinus volume, ostium diameter and ostium canal length of maxillary sinus, and the sinus volume, ostium diameter, and ostium canal length of frontal sinus, respectively). The high \( P \) values (all >0.05) indicate that there are no statistically significant correlations between the area overestimation with AR and the paranasal sinus volume and ostium size.

Finally, we estimated the fundamental resonant frequencies of the subjects’ paranasal sinuses by using the well-known theory of the Helmholtz resonator (20). This theory stipulates that both the diameter \( d \) and length \( l \) of the resonator’s neck must be small compared with the sound wavelength \( \lambda \). The paranasal sinus ostia of all subjects in our study met this condition. According to the theory, if both \( d \) and \( l \) of the neck are small compared with \( \lambda \), the fundamental resonant frequency \( f_0 \) of a Helmholtz resonator is given by (1, 20)

\[
f_0 = \frac{c}{2\pi} \sqrt{\frac{S}{V(l + 0.85d)}}^{1/2}
\]

Here, \( c = 34,300 \text{ cm/s} \) is the velocity of sound in air, \( S = \pi d^2/4 \) is the cross-sectional area of the neck, and \( V \) is cavity volume (see Fig. 3). In the derivation of Eq. 2, no assumption was made about the shape of the resonator cavity. For any
given neck, it is the volume of the resonator cavity, not its shape, that is important in determining the fundamental resonant frequency. In fact, as long as the linear dimensions of the cavity are considerably smaller than the sound wavelength and the neck diameter is not too large, the fundamental resonant frequencies of cavities that have different shapes but identical neck sizes and volumes are the same (20). This suggests that Eq. 2 can be applied to paranasal sinuses of any shape.

We calculated the fundamental resonant frequencies of the maxillary and frontal sinuses for each of the 20 nasal passages by inserting the CT data for ostium size and sinus volume (Tables 1 and 2) into Eq. 2. The results indicated resonant frequencies ranging from ~110 to 350 Hz for the maxillary sinuses and from 160 to 1,240 Hz for the frontal sinuses. All these frequencies were in the frequency bandwidth (100–10,000 Hz) of the AR instrument we used in the study. This finding is central to the discussion of possible reasons for AR area overestimation beyond paranasal sinus ostia.

**DISCUSSION**

It is important to know the extent to which the paranasal sinuses influence area-distance curves measured by AR, because this information may be useful when investigating sinus ostia or sinus pathology. To our knowledge, Kase and colleagues (18, 19) were the first to investigate how the paranasal sinuses affect AR measurements. This group tested a tube model with a side hole to which a syringe was attached, and they concluded that AR is valuable for assessing the paranasal sinuses when the sinuses communicate with the nasal cavity via large openings. In a clinical study, Marais and Maran (21) used AR to examine 25 patients who had undergone inferior meatal antrostomy. They noted that AR did not demonstrate changes in sinus volume or the size of the antrostomy opening and attributed this to an umbrella-like protective effect of the inferior turbinate over the antrostomy site.

Hilberg and Pedersen (14) evaluated the effects of paranasal sinuses on AR using pipe models, a stereolithographic model with open sinuses, and living subjects. The pipe models had a side hole, the diameter of which could be altered from 1.2 to 8.0 mm. The hole was opened into a finite “sinus” volume of 20 cm³. Their experiments showed that the side hole larger than 2.2-mm diameter had a significant effect on the AR data, such that the cross-sectional areas of the pipe at 20 mm beyond the hole were overestimated by more than 100%. These authors also found that the cross-sectional areas of the stereolithographic model distal to the sinus ostium were influenced by ostium size. They concluded that loss of sound to the paranasal sinuses (and the maxillary sinuses in particular) significantly influences the AR area-distance curve in the posterior part of the nasal cavity and noted that this effect is greater when the sinus ostium is large.

In a study of six living human subjects with decongested sinus orifices, Terheyden and coworkers (25) showed that the correlation between area-distance curves derived by AR and CT decreased at distances >6.0 cm from the nostril, with AR overestimating the true areas by more than 100%. They, too, concluded that the openings to the paranasal sinuses are sites of sound loss and that these losses significantly affect the estimation of cross-sectional areas beyond the sinus ostia. However, they stressed that sound loss through the sinus openings does not fully explain the degree of overestimation that occurs with AR in the posterior part of the nasal cavity.

Djupesland and Rotnes (8) studied the effects of paranasal sinuses on AR measurements using a stereolithographic model of a human nasal cavity. Their study demonstrated that ostium size and the volume of the communicating sinus have some influence on AR-derived cross-sectional areas and volumes posterior to the sinus ostia. They observed that the larger the ostium and sinus volume, the greater the effect on AR measurements.

However, until recently, interpretation and discussions of the effects of paranasal sinuses on AR results (8, 14, 18, 19, 23, 25) had been qualitative and had been based solely on experimental data. No attempts had been made to theoretically interpret the experimental AR data. Cakmak et al. (1) published an experimental and theoretical study in 2003 that involved the use of pipe models with a Helmholtz resonator as a side branch, simulating a paranasal sinus. Those data showed that AR overestimates cross-sectional areas posterior to the simulated sinus ostium to a degree that depends on ostium size and/or paranasal sinus volume. In addition to overestimation of area, the AR-measured area-distance curves beyond the simulated ostium showed pronounced oscillations. The authors also found that the simulated paranasal sinus of any volume and ostium of any size had no measurable effect on the area-distance curve for the portion of the nasal passage anterior to the ostium. Cakmak and colleagues (1) theoretically proved that the oscillating pattern of the curve beyond the side branch is caused by acoustic resonances in this portion of the pipe. They argued that AR area overestimation is not due to loss of sound power into the side branch. They concluded that the algorithms used in AR do not account for the effects of the asymmetrical branching represented by paranasal sinuses connected to the nasal cavity via sinus ostia.

In our present clinical study, we found that both the area overestimation and oscillation of the AR-derived area-distance curve beyond the paranasal sinus ostia were common to all 20 nasal passages investigated. This suggests that these two AR phenomena are inherent to the physics of sound-wave transmission through the human nasal cavity (1, 4, 5).

To understand the causes of area overestimation with AR and the causes of AR-derived area-distance curve oscillation beyond the sinus ostia, it is necessary to review the physical elements of the technique. The physical principle of acoustic pulse reflectometry is that sound waves propagating in a tube are reflected when there are local changes in acoustic impedance that result from changes in the cross-sectional area of the tube (9, 11, 13, 15–17). The sound waves undergo partial reflection and partial transmission at each place along the tube where there is change in acoustic impedance, thus creating a reflection sequence. The reflection sequence at the input to the tube is termed the “input impulse response” of the tube, and from this one can calculate cross-sectional area as a function of axial distance (9, 11, 17). Experimental data for input impulse response are usually converted to an area-distance curve by using the algorithm developed by Ware and Aki (27).

The sound waves transmitted through the nasal valve undergo multiple reflections at all locations where the acoustic impedance changes, including the openings to the paranasal sinuses. Hence, superposition of the sound waves traveling in opposite directions within the nasal cavity generates a compli-
cated pattern of standing waves, particularly in the portion of the nasal cavity posterior to sinus ostia. By considering the actual size (effective diameter and length) of the portion of human nasal cavity beyond the sinus ostia, we estimated the fundamental resonant frequency of the nasal cavity to be close to 2,900 Hz. This means that the fundamental resonant frequency and the first two overtones of the distal portion of the nasal cavity extend well into the frequency bandwidth of the acoustic rhinometer. Therefore, the oscillations of the area-distance curve measured by AR (i.e., the maxima M1 and M2 in Figs. 4 and 5) are due to these acoustic resonances in the posterior nasal cavity. However, because the incident sound pulse produced by the acoustic rhinometer contains a homogeneous frequency spectrum from 100 Hz to 10 kHz, it is difficult to calculate the actual locations of the pressure nodes and antinodes. Cankurtaran and coworkers (4) demonstrated that, for a plane sound wave of frequency $f$ (= c/$\lambda$), the distance between two consecutive pressure antinodes (nodes) in a pipe of finite length is equal to $\lambda/2$. The AR area-distance curves obtained for all of the nasal cavities in the present study featured local maxima at every 11 to 12 data points (see Fig. 4). The AR instrument produces a data point every 0.24 cm, implying that $\lambda \approx 5.8$ cm, which corresponds to a frequency of $\sim 5,950$ Hz (roughly equal to that of the first overtone, mentioned above). Indeed, the axial distance between the maxima M1 and M2 on the AR area-distance curves for the nasal cavities we studied was roughly 3.0 cm, which is approximately one-half the wavelength of the first overtone. This further supports the suggestion that the oscillations of the AR-derived area-distance curve in the portion of the nasal cavity beyond the sinus ostia are due to acoustic resonances in this region.

AR area overestimation beyond the sinus ostia is closely related to the interaction between the nasal cavity and the paranasal sinuses. Cakmak and coworkers (1) argued that there is no net dissipation of sound energy from the sinus ostia into the paranasal sinuses, because all sound energy that is absorbed by the sinuses during certain parts of the acoustic cycle is returned to the nasal cavity in other parts of the cycle. 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 Ware-Aki algorithm as area overestimation.

In summary, although the opening to a paranasal sinus causes a significant change in the acoustic impedance of the nasal passage at that site, the average sound power loss to the sinuses is negligible. It is the complex acoustic impedances of the paranasal sinuses and the nasal cavity that are most important in AR determination of cross-sectional area beyond the sinus ostia. Our present experimental results for living human subjects reveal that the complex acoustic impedances of the paranasal sinuses and nasal cavity (and, hence, the effects of acoustic resonances in the sinuses and posterior nasal cavity) are not accounted for in the AR algorithms used today. As a consequence, AR does not provide quantitative information about paranasal sinus volume or ostium size and markedly overestimates cross-sectional areas in the distal parts of nasal cavity.

In conclusion, the results we obtained for living human subjects in this study suggest that, when the nasal valve passage area is within the normal adult range, AR is a valuable method for measuring the cross-sectional areas of the nasal cavity anterior to the paranasal sinus ostia. However, AR overestimates cross-sectional areas in the portion of the nasal cavity beyond sinus ostia larger than $\sim 0.10$ cm diameter. This effect is independent of sinus volume. The area overestimation is due to interaction between the nasal cavity and paranasal sinuses, not to loss of sound power into the sinuses via the ostia. AR does not provide quantitative information about the paranasal sinuses (i.e., ostium size or sinus volume) and grossly overestimates cross-sectional areas in the nasal cavity posterior to the ostia. Consequently, the diagnostic value of this method is limited to the anterior nasal cavity.

GRANTS

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