Effects of paranasal sinus ostia and volume on acoustic rhinometry measurements: a model study

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Cakmak, Ozcan, Huseyin Çelik, Mehmet Cankurtaran, Fuat Buyuklu, Nuri Özgirgin, and Levent Naci Ozluoglu. Effects of paranasal sinus ostia and volume on acoustic rhinometry measurements: a model study. J Appl Physiol 94: 1527–1535, 2003. First published December 13, 2002; 10.1152/japplphysiol.01032.2002.—We used pipe models to investigate the effects of paranasal sinus ostium size and paranasal sinus volume on the area-distance curves derived by acoustic rhinometry (AR). Each model had a Helmholtz resonator or a short neck as a side branch that simulated the paranasal sinus and sinus ostium. The AR-derived cross-sectional areas posterior to the ostium were significantly overestimated. Sinus volume affected the AR measurements only when the sinus was connected via a relatively large ostium. The experimental area-distance curve posterior to the side branch showed pronounced oscillations in association with low-frequency acoustic resonances in this distal part of the pipe. The experimental results are discussed in terms of theoretically calculated “sound-power reflection coefficients” for the pipe models used. The results indicate that the effects of paranasal sinuses and low-frequency acoustic resonances in the posterior part of the nasal cavity are not accounted for in the current AR algorithms. AR does not provide reliable information about sinus ostium size, sinus volume, or cross-sectional area in the distal parts of nasal cavity.

nasal cavity; sinus ostium; Helmholtz resonator; sound-power reflection coefficient

ACOUSTIC RHINOMETRY (AR) was introduced by Hilberg et al. (11) in 1989 as an objective method for measuring the dimensions of the nasal cavity. As a simple and noninvasive technique, AR became widely accepted in a short period of time. However, there are some physical limitations associated with the algorithms used in AR, and these have not been fully addressed to date. Most previous investigations of living human subjects or cadavers 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 modalities such as MRI and computerized tomography (CT). However, this does not hold true for the posterior part of the nasal cavity and the epipharynx, where AR significantly overestimates the cross-sectional areas compared with MRI and CT. A previous report by Cakmak et al. (3) (and references therein) documents these differences.

One possible explanation for the discrepancy is sound loss through the ostia into the paranasal sinuses, which would lead to AR overestimation of the cross-sectional area of the nasal cavity distal to the sinus ostia (5, 7, 13, 19, 20, 24, 25). 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 the paranasal sinus ostia or pathologies involving the sinuses themselves. Several studies have focused on ways in which the paranasal sinuses influence the area-distance curves determined by AR (5, 7, 13, 19, 20, 24). However, the physical basis for the inaccuracy of some of these area-distance curves, particularly those in the posterior part of nasal cavity, is still not completely understood. Further model studies are needed to determine how the paranasal sinuses and ostia influence AR measurements.

In this study, we used pipe models to investigate the effects of paranasal sinus ostium size and paranasal sinus volume on the area-distance curves derived by AR. Each model had a Helmholtz resonator or a short neck (no resonator cavity attached) as a side branch. The experimental results are discussed in terms of theoretically calculated “sound-power reflection coefficients” for the pipe model variations that were used. Particular emphasis was placed on determining the reasons for area overestimation and for the oscillation in the parts of the area-distance curves that corresponded to the section of pipe beyond the side branch.

MATERIALS AND METHODS

A transient signal acoustic rhinometer (Ecco Vision, Hood Instruments, Pembroke, MA) was used to perform the acoustic measurements. To assess the influence of ostium size and sinus volume on AR measurements, pipe models simulating the nasal passage anatomy were manufactured (Fig. 1). Each model consisted of a brass pipe (12 cm long; 1.2-cm internal diameter) with a short neck that branched off and opened

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into an enclosed cavity. This attached acoustic system is commonly known as a Helmholtz resonator (21), and its neck and cavity represent the sinus ostium and the sinus volume, respectively. All the models were identical except for neck diameter and cavity volume. In each case, the Helmholtz resonator was connected to the main pipe at the same distance (6.0 cm) from one end of the pipe. The inner neck diameters and the cavity volumes that were used were comparable to the sizes of adult paranasal sinus ostia and adult paranasal sinus volumes, respectively.

Five pipe models were constructed, each with a 1.65-cm-long neck made of brass. The internal diameters of the five necks were 0.15, 0.3, 0.5, 0.7, and 0.9 cm, respectively (Fig. 1A). In each model, measurements were made with the neck connected to each of seven cylindrical cavities of different volumes (3.0, 4.6, 7.1, 8.6, 11.9, 16.8, and 21.1 cm³, respectively) (Fig. 1B). To simulate the nasal valve, a cylindrical insert that was 0.5 cm long and had an inner passage area of 0.60 cm² (approximately equal to adult nasal valve area) was placed 2.0 cm from the left end of the pipe. The diameter (2b) of the main pipe was fixed. The left end of the main pipe was connected to the nosepiece of the acoustic rhinometer.

To prevent acoustic leakage, secure contact between the nosepiece of the rhinometer and the pipe model was maintained during all experiments. The nosepiece of the rhinometer was attached at the “anterior” end of the main pipe, which represented the start of the sound pathway. The simulated nasal valve (where present) was positioned 2.0 cm posterior to the anterior end of the model, and the side branch was located 6.0 cm posterior to the anterior end. All AR measurements were repeated at least five times to ensure the results were reproducible. Data collected from the examinations were analyzed by using Origin software (version 6.0, Microcal Software).

RESULTS

AR results vary significantly depending on the neck diameter and cavity volume of the Helmholtz resonator, which were the two independent variables in our pipe models. Figure 2 shows how the experimental area-distance curves varied with neck diameter in models with cavity volumes of 3.0 and 11.9 cm³, respectively. Figure 3 shows how the area-distance curves varied with cavity volume in models with neck diameters of 0.3 and 0.9 cm, respectively. On each area-distance curve, the first minimum corresponds to the

![Fig. 1. The shape and dimensions of the pipe models consisting of a main pipe (12 cm long and 1.2-cm internal diameter) with an orifice (A) and a Helmholtz resonator (B) as side branch. The neck diameter (2a) and the cavity volume (V) were variable. A cylindrical insert with 0.60 cm² inner passage area was placed 2.0 cm from the left end of the pipe. The diameter (2b) of the main pipe was fixed. The left end of the main pipe was connected to the nosepiece of the acoustic rhinometer.](image)

![Fig. 2. The effects of 2a on the experimental area-distance curves for pipe models with a Helmholtz resonator of V = 3.0 cm³ (A) and 11.9 cm³ (B). The different symbols refer to data sets obtained for models with different 2a, as shown inside the panels. Lines of best fit have been drawn to help guide the eye.](image)
were approximately equal to the actual value of the cross-sectional areas beyond the branching point regardless of cavity volume, the experimental AR-de-tracts. Our findings suggest that AR provides reliable data for cross-sectional area in the anterior acoustic pathway until branching, such as a sinus opening, to the side branch were similar and varied only minimally to the branch were similar and varied only minimally.

When the neck was open, the cross-sectional areas beyond the side branch were consistently overestimated, and the curves showed oscillations similar to those noted in Figs. 2 and 3. In this case, the area-distance curves deviated markedly from each other at more distal points (>80 cm), and the oscillation amplitude increased substantially in this section of the curves as well (Fig. 3B). One potential problem in using AR to study the geometry of the nasal cavity is that cross-sectional areas beyond a severe constriction may not be estimated accurately (1, 2, 11, 12, 24). In one set of experiments, we examined pipe models that had Helmholtz resonators attached but no nasal valve simulator. The aim was to assess the effects of the nasal valve on AR measurements and on the oscillation of the area-distance curve beyond the side branch. The experimental area-distance curves showed the same general trend as was observed in the models that had nasal valve inserts. In particular, the cross-sectional areas beyond the side branch were consistently underestimated, and the curves showed oscillations similar to those noted in Figs. 2 and 3. Overall, absence of the insert (inner passage area of 0.60 cm²) did not significantly alter the main features of experimental area-distance curves beyond the side branch.

To investigate the influence of the sinus ostium alone on the area-distance curve, we used pipe models that had no resonator cavity (sinus) (Fig. 1A) and recorded AR measurements with the short neck (sinus ostium) open or closed. The area-distance curves obtained for the models with the ostium open and closed are shown in Fig. 4, A and B, respectively. The AR results anterior to the branch were similar and varied only minimally with neck diameter, as was observed for the models that had the Helmholtz resonator as a side branch. When the neck was relatively narrow (<=0.3 cm), the experimental cross-sectional area beyond the side branch was only slightly altered by cavity volume (Fig. 3A). When the neck was wider (0.5 ≤ neck diameter ≤ 0.9 cm), an increase in cavity volume had a greater effect. In this case, the area-distance curves deviated markedly from each other at more distal points (>8.0 cm), and the oscillation amplitude increased substantially in this section of the curves as well (Fig. 3B).

The most striking feature of the experimental data presented in Figs. 2 and 3 is that the cross-sectional areas beyond the side branch oscillate with distance. These fluctuations were evident even in the model with the narrowest neck. For a given cavity volume, the amplitude of the oscillations increased substantially with increasing neck diameter (Fig. 2). However, the locations of the oscillation peaks and, hence, the oscillation period (in units of length) appeared to be unrelated to neck diameter and cavity volume. When the neck was relatively narrow (<=0.3 cm), the experimental cross-sectional area beyond the side branch was only slightly altered by cavity volume (Fig. 3A). When the neck was wider (0.5 ≤ neck diameter ≤ 0.9 cm), an increase in cavity volume had a greater effect. In this case, the area-distance curves deviated markedly from each other at more distal points (>8.0 cm), and the oscillation amplitude increased substantially in this section of the curves as well (Fig. 3B).

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The theory of sound-wave transmission through a pipe of finite length with a side branch provides some insight into the physical basis for overestimation of cross-sectional area beyond the side branch and for oscillation in the corresponding section of the area-distance curve. Because AR is based on the reflection of sound waves due to local changes in acoustic impedance, we derived an expression for a "sound-power reflection coefficient." This theory is an integral component of our interpretation and discussion of the experimental data; hence, it is briefly outlined in the next section. After this explanation of the theory, the experimental results are discussed within this theoretical framework.

**Theory of sound-wave propagation in a pipe with a side branch.** The following analysis of the propagation of plane sound waves through pipes assumes that the cross-sectional dimensions of all pipes are small compared with the sound wavelength (\( \lambda \)). This assumption is valid for all pipe models examined in the present work, since the shortest \( \lambda \) produced by the AR instrument is \( \approx 3.43 \) cm. Therefore, there is no need to consider the diffraction effects when AR measurements are analyzed (2, 9, 21).

We shall first consider the influence of an arbitrary side branch on the transmission of acoustic waves through a rigid pipe of finite length and uniform cross section (Fig. 1). The presence of such a branch causes the acoustic impedance at the junction to differ from \( z = \rho_0 c S / Z \), the characteristic impedance for plane waves in a pipe, where \( \rho_0 \), \( c \), and \( S \) are the density of air, sound velocity in air, and cross-sectional area of the pipe, respectively. Consequently, a reflected wave is produced (9, 21). Furthermore, a portion of the incident acoustic power may be transmitted into and dissipated within the branch. Both of these factors contribute to a reduction in the acoustic energy transmitted through the section of pipe beyond the branch.

Applying the usual conditions of continuity of pressure and volume velocity at the junction where the acoustic impedance changes, we derived an expression for the ratio of the pressure amplitude (\( B_1 \)) of the reflected wave to that of the incident wave (\( A_1 \))

\[
B_1 = \frac{S}{\rho_0 c} \frac{Z_t Z_b - (Z_t + Z_b)}{Z_t Z_b + (Z_t + Z_b)}
\]  

Here, \( Z_t \) is the input acoustic impedance of the pipe section beyond the branch, and \( Z_b \) is the acoustic impedance of the branch. The sound-power reflection coefficient (\( \alpha_r \)) is defined by (21)

\[
\alpha_r = \left( \frac{B_1}{A_1} \right)^2
\]

The input acoustic impedance of a pipe of length \( L \) and terminal impedance (\( Z_L \)) is given by (9, 21, 23)
Eqs. 3 and beyond the branch can be rewritten as that at which the reactive component of the sound waves traveling in opposite directions generates patterns of standing waves in the portion of the main pipe beyond the junction. The resonant frequency of the open-ended, unflanged pipe is given by

\[ Z_t = \frac{\rho_0 c}{S} \frac{Z_L + j \frac{\rho_0 c}{S} \tan kL}{\frac{\rho_0 c}{S} + jZ_L \tan kL} \]  

where \( j = (-1)^{1/2} \). It is clear from this equation that the \( Z_t \) in the transmitted wave is a complex quantity and depends not only on the terminating impedance \( Z_L \) but also on the \( L \) of the pipe beyond the branch and the wave constant \( k = 2\pi/\lambda \). At low frequencies, where \( 2kB < 0.5 \), a condition that is satisfied to a large extent for all the pipe models used in the present study, the terminal acoustic impedance of an unflanged, open-ended pipe is approximately equal to

\[ Z_L = \frac{\rho_0 c}{S} (\alpha + j\beta) \]  

where \( \alpha = k^2b^2/4 \) and \( \beta = 0.6kb \) (21). By combining Eqs. 3 and 4, the input impedance of the pipe section beyond the branch can be rewritten as

\[ Z_t = R_t + jX_t = \frac{\rho_0 c}{S} \frac{\alpha + j(\tan kL + \beta)}{(1 - \beta \tan kL) + j\alpha \tan kL} \]  

Because the main pipe beyond the branch is of finite length, some amount of the incident sound power is reflected back from its open end. Hence, superposition of the sound waves traveling in opposite directions generates patterns of standing waves in the portion of the main pipe beyond the junction. The resonant frequency is defined as that at which the reactive component \( X_t \) of the input impedance vanishes. At low frequencies, where both the real and imaginary components of \( Z_t \) are small, it can be shown from Eq. 5 that the resonant frequencies of an open-ended, unflanged pipe of length \( L \) are given by

\[ f_n = n f_1, \quad n = 1, 2, 3, \ldots \]  

where

\[ f_1 = \frac{c}{2(L + 0.6b)} \]  

is the fundamental resonant frequency. The overtones of an open-ended pipe form an integral harmonic group.

The first five resonant frequencies of the portion of the open-ended main pipe beyond the branch, as calculated by using Eqs. 6 and 7 (with \( c = 34,300 \) cm/s, \( b = 0.6 \) cm, and \( L = 6 \) cm), are summarized in Table 1. As the table shows, the fundamental, first, and second harmonics fall within the frequency bandwidth of the AR instrument; the third overtone is just at the upper border or slightly out of the range; and the fourth overtone is well out of the range.

According to Eq. 3, \( Z_t \) oscillates as a function of sound frequency. For a source of constant pressure amplitude, whenever the incident sound wave has a frequency component that corresponds with the resonant frequency \( f_n \) of the main pipe beyond the branch, its \( Z_t \) attains a minimum and the sound power radiated out of its open end becomes a maximum (21). If the sound frequency does not coincide with one of the resonant frequencies, only a small percentage of the incident acoustic power is transmitted out of the pipe; the remainder is reflected back down the pipe. As a consequence, consecutive minima and maxima would be expected to appear in the plot of sound-power reflection coefficient vs. sound frequency.

In applying the theory outlined above to our present study, we first consider the effect of using a Helmholtz resonator as a side branch (Fig. 1B). The Helmholtz resonator consists of a rigid cavity of volume (V) that communicates with the external medium (i.e., the air in the main pipe) through a short neck/opening of radius \( a \) and length \( l \). If both the radius \( a \) and length \( l \) of the neck are small compared with the sound \( \lambda \), the branch impedance of a Helmholtz resonator can be represented by (4, 9, 21)

\[ Z_b = R_b + jX_b = \frac{\rho_0 c k^2}{2\pi} + j \left( \frac{\rho_0 a l}{V} - \frac{\rho_0 c^2}{\omega V} \right) \]  

Here \( \omega = 2\pi f \) is the angular frequency of the sound wave, \( l' = l + 1.7a \) is the effective length of the neck, and \( S_b = \pi a^2 \) is the cross-sectional area of the opening into the resonator. The first term on the right-hand side of Eq. 8 results from the radiation of sound through the neck into the cavity. The second term results from the inerterance of the air in the neck and that in the cavity. If the opening to the cavity is merely a hole drilled in the thin wall of the main pipe, \( l = 0 \), and hence \( l' \) has a minimum value of 1.7a.

The resonant frequency \( f_0 \) of a Helmholtz resonator is defined as the frequency at which the reactive component \( X_b \) of its impedance vanishes. Applying this condition to Eq. 8, we obtain

\[ f_0 = \frac{c}{2\pi} \left( \frac{S_b}{l'} \right)^{1/2} \]  

The resonant frequency of the Helmholtz resonators that we used in this study ranges from \( \sim 120 \) to 1,400 Hz and falls in the frequency range of the AR instrument. However, the \( f_0 \) values are much smaller than the fundamental frequency of the portion of the main pipe beyond the side branch (see Table 1). Whenever the incident sound wave has a frequency component that corresponds to the resonant frequency of the Helmholtz resonator, all acoustic energy that is trans-
mitted into the cavity from the incident sound wave returns to the main pipe with such a phase relationship as to be reflected back toward the source (21).

The sound-power reflection coefficient \( \alpha_r \) of pipe models that have a Helmholtz resonator as a side branch would be expected to exhibit a complicated dependence on sound frequency due to the combined effects of the acoustic resonances in both the Helmholtz resonator and the main pipe beyond the branch. By incorporating Eqs. 2, 5, and 8, we calculated \( \alpha_r \) as a function of sound-wave frequency for selected neck diameters and cavity volumes. All calculations were performed by using Mathcad mathematical software (Mathcad 2001 professional, Mathsoft). For models with a Helmholtz resonator and with the main pipe open at its terminal end, when the sound frequency is increased from 100 Hz to 10 kHz, the sound-power reflection coefficient oscillates markedly while gradually decreasing (Fig. 5). For a given cavity volume, the amplitude of the oscillations increases considerably as neck diameter increases (Fig. 5A). Careful inspection of Fig. 5A reveals that the oscillations are discernible even in the \( \alpha_r(f) \) curve that corresponds to the model with the narrowest neck. It is also interesting to note that, for a given neck diameter in the frequency range above ~3 kHz, the sound-power reflection coefficient is not altered by changes in cavity volume (Fig. 5B). Because AR measures the intensity of reflected sound waves and compares it with that of incident sound waves, one would expect the AR-derived cross-sectional areas beyond the branch to be significantly overestimated and to oscillate. Overestimation of area can be attributed to loss of sound power through the open end of the main pipe and through the branch. However, with Helmholtz resonators, even when the sound frequency does not coincide with the resonant frequency of the resonator, the sound-power losses due to viscosity forces and to radiation of sound into the resonator cavity are very small (9, 21). Hence, if losses due to radiation and viscosity are neglected, there is no net dissipation of energy from the neck into the Helmholtz resonator: All sound energy absorbed by the resonator during some parts of the acoustic cycle is returned to the main pipe during other parts of the cycle. This argument explains the very small decrease in the \( \alpha_r(f) \) curve that is observed in the frequency range below ~1 kHz, which depicts the effect of the Helmholtz resonator (Fig. 5). In summary, the area overestimation beyond the side branch is essentially due to loss of sound power out the open end of the main pipe rather than through the neck into the Helmholtz resonator. The oscillation of the sound-power reflection coefficient with frequency and the oscillation of the experimental area-distance curves measured by AR are closely related to each other and are mainly governed by the acoustic resonances in the portion of the main pipe beyond the branch.

Next, we consider the effect of an orifice (a short pipe) as a side branch, which simulates a sinus ostium without the sinus (Fig. 1A). If both the radius \( a \) and the length \( l \) of the orifice are small compared with the sound \( \lambda \), the branch impedance of such an orifice can be approximated by (21)

\[
Z_b = R_b + jX_b = \frac{\rho_0 c k^2}{2\pi} + j \frac{\rho_0 l \omega}{\pi a^2} \quad (10)
\]

The first term on the right-hand side of Eq. 10 results from the radiation of sound through the orifice into the external medium; the second term results from the inerterance of the gas in the orifice. The calculated \( \alpha_r(f) \) curves for pipe models with an orifice as a side branch and the main pipe open at its terminal end (Fig. 6) exhibit features similar to those observed with the corresponding models that had Helmholtz resonators attached. This indicates that, regardless of the nature of the branch (resonator cavity attached or unattached), AR overestimates the cross-sectional areas beyond the branch point and that oscillation of the experimental area-distance curves is due mainly to the acoustic resonances in the pipe section beyond the branch.

Fig. 5. The relationship between calculated sound-power reflection coefficient and frequency for pipe models with a Helmholtz resonator as a side branch and with the terminal end of the main pipe open. Plots for selected \( 2a \) (A) and \( V \) (B) are shown.

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DISCUSSION

It is important to establish whether AR measurements provide valuable information about the state of the paranasal sinuses and the ostia that connect them with the nasal cavity. There is evidence that cross-sectional areas at distances of ~5–10 cm into the nasal cavity do reflect the state of these sinuses, and particularly the ostia (14). Although several reports on this subject have been published, it is still not entirely clear how the paranasal sinuses influence AR-derived area-distance curves. Critical review of the relevant literature reveals that most previous interpretations and discussions have been qualitative and based solely on experimental data. Specifically, investigators have compared experimental AR area-distance curves with those obtained by imaging techniques, such as MRI and CT. However, no attempts have been made to theoretically interpret the experimental AR data.

To the best of our knowledge, the influence of the paranasal sinuses on AR measurements was first studied by Kase et al. (19), who used a model that consisted of an acrylic tube with a side hole to which a syringe was attached. Their conclusion was that AR is of value for assessing the paranasal sinuses when the sinuses communicate with the nasal cavity via large openings. In another study, Kase and co-workers (20) demonstrated that the volume of the paranasal sinus influences AR results only if the middle meatus or an alternative communication pathway is fully patent. In a clinical study, Marais and Maran (22) 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. The authors (22) attributed this to an umbrella-like protective effect of the inferior turbinate over the antrostomy site.

In their investigation of the effects of paranasal sinuses on AR, Hilberg and Pedersen (13) took measurements by using pipe models, a stereolithographic model with open sinuses, and living subjects. The pipe model had a side hole, the diameter of which could be altered in a range from 1.2 to 8.0 mm. The hole was opened into a finite “sinus” volume of 20 cm³. Their experiments showed that a side hole of ~2.2-mm diameter had a significant effect on the AR data, such that the cross-sectional areas of the tube at 20 mm beyond the hole were overestimated by >100%. For some of the living subjects examined in that study, the AR curves were in good agreement with the area-distance curve in the stereolithographic model. Hilberg and Pedersen (13) noted 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 living subjects with decongested sinus orifices, Terheyden et al. (24) showed that the correlation between the area-distance curves measured by AR and CT decreased at distances of >6.0 cm, with AR overestimating the true areas. The authors 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 past the sinus ostia. However, they also 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.

Recently, Djupesland and Rotnes (7) explored the effects of paranasal sinuses on AR measurements by using an epoxy model that was created from a digital voxel model of a human nasal cavity. Their study demonstrated that ostium size and the volume of the communicating sinus has some influence on AR-derived cross-sectional area and volumes posterior to the sinus ostia. They observed that the larger the ostium and sinus volume, the greater the effect on AR measurements.

The results of our present study confirm those in most of the reports summarized above. They indicate that the paranasal sinuses and ostia have no measurable effect on the area-distance curve anterior to the sinus ostia and that AR overestimates the cross-sectional area posterior to the ostia. Our results also show that small ostia have only a limited effect on AR measurements, whereas larger openings cause the cross-sectional area posterior to the ostia to be greatly overestimated. The volume of the sinus is another parameter that affects AR measurements posterior to the sinus ostia. However, the influence of sinus volume is significant only when the sinus ostium is large. Overestimation of the area beyond the ostium becomes more exaggerated as ostium diameter increases or sinus volume increases. In addition to overestimation of area, the experimental area-distance curves beyond the side branch show pronounced oscillations.

The overestimation of cross-sectional area beyond the side branch and the presence of oscillations can
both be quantitatively explained on the basis of the theory of transmission of acoustic waves through a finite pipe with a side branch and by considering the assumptions made in the algorithms used in AR. The theoretical assumptions (8, 15, 16, 17) that are necessary to compute cross-sectional areas from the acoustic-pulse response may not all be valid when the actual geometry of the nasal cavity is measured (11). The first assumption that sound waves propagate as plane waves is probably true in the nasal cavity because its cross-sectional dimensions are smaller than the sound λ. The second assumption is that accurate estimates of area can only be obtained for structures with rigid walls. This is also valid because the nasal cavity has a relatively rigid structure even though it is lined with fairly soft mucosa (4, 12). The third assumption is that viscous losses, especially those related to the convoluted geometry of the nasal cavity, are negligible. Previous studies that have applied both transient and continuous AR have shown that the complex geometry of the nasal cavity (i.e., changes in its shape and effective diameter) has no significant impact on AR measurements (6, 12). In summary, all three of these assumptions are valid for the pipe models that we used in our study.

The fourth assumption that is fundamental to the algorithms used in AR is that any bifurcations (branching) are symmetrical (8, 11, 15–17). In other words, the algorithms used in AR assume that there is no asymmetrical branching that could cause parts of the incident sound wave to be lost to analysis (6). Our theoretical results for sound-power reflection coefficient (Figs. 5 and 6) indicate that this assumption is not valid for pipe models with a single side branch. When a passage-way being analyzed by AR does not meet this assumption, the area posterior to any side branch would be overestimated. As we found, area overestimation was strongly correlated with ostium size and sinus volume in our pipe models. In brief, 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. Asymmetric branching is also encountered at the distal end of the nasal septum where the two nasal passages join (6, 11, 24, 25). However, experimentation with tube models has shown that the contribution of this form of branching is of minor importance (13, 24).

The experimental AR curves for all the pipe models that we investigated in this study showed pronounced oscillation beyond the branching point. Although the oscillation amplitude varied dramatically in relation to neck diameter and cavity volume, the oscillation period (in units of length) was roughly constant. The latter also did not change according to the nature of the side branch (presence or absence of attached sinus). Many authors (1, 2, 10) have reported oscillations in area-distance curves for pipe models that have an aperture simulating the nasal valve but no side branch. The area-distance curves we obtained for our models show relative maxima at every eight to nine experimental data points. The AR instrument produces a data point every 0.24 cm, implying that high-frequency acoustic resonance may be causally related to the oscillations, as noted previously (1). However, because the acoustic signal is already filtered with a 10-kHz low-pass filter (as set by the manufacturer), high-frequency acoustic resonance, such as cross modes, cannot be the source of the oscillations (12, 17). Buentering et al. (1) argued that the oscillations must originate from the mathematical deconvolution of the digitized signal or from low-frequency acoustic resonance, but they gave no satisfactory theoretical explanation for this reasoning.

As established in the theoretical analysis above, the oscillating pattern that we observed originates mainly from low-frequency acoustic resonances in the main pipe beyond the side branch. A similar interpretation may apply to the human nasal cavity since its acoustic pathway is also of finite length. Our results suggest that AR area overestimation beyond the sinus ostium is mainly due to sound loss through the distal end of the nasal cavity rather than from loss through the sinus ostia into the paranasal sinuses. When the incident sound wave has a frequency component that corresponds to one of the resonant frequencies of the nasal cavity posterior to the sinus ostium, its input impedance becomes minimal and the sound power radiated out of the distal end of the cavity reaches maximum. If the sound frequency does not coincide with one of the resonant frequencies of the section of nasal cavity posterior to the sinus ostium, only a small percentage of the incident acoustic power is transmitted out of the nasal cavity. The remainder is reflected back toward the source. On this basis, one would expect the sound-power reflection coefficient of the nasal cavity to oscillate as a function of sound frequency. This oscillation of the reflected sound power would, in turn, also cause the cross-sectional area measured by AR to fluctuate, which is what we observed experimentally.

It must be emphasized that the acoustic impedance of the nasal cavity beyond the sinus ostium is complex and can be approximated by Eq. 3 rather than by \(\rho cS(x)\), as assumed in the algorithms of AR (16). The results of the model calculations that we have presented here suggest that there is a need for further improvement in the design of the AR equipment and related computer software. The complex impedances of the paranasal sinuses and ostia (see Eqs. 8 and 10) and the finite length of the nasal cavity (and, hence, the corresponding low-frequency acoustic resonances) must be considered in the algorithms for this technique (8, 15, 16, 17). Our theoretical considerations show that, although the opening to the paranasal sinuses causes a significant change in the acoustic impedance at the junction, the average sound loss to the sinuses is very small. This implies that it is the side-branch impedance, and not the loss of sound power to the paranasal sinuses, that is important in determining cross-sectional area beyond the sinus ostium. Our results supported this.

When the expression for the fundamental resonant frequency of a Helmholtz resonator (Eq. 9) was derived, no assumption concerning the shape of the resonator cavity was made. For a given opening, it is the...
volume of the cavity and 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 λ and the opening is not too large, the fundamental resonant frequencies of cavities that have different shapes but identical opening sizes and volumes are the same (21). This suggests that the theory presented above can be applied to a cavity of any shape, including the paranasal sinuses.

Conclusions. We carried out AR measurements by using a series of pipe models with a side branch in the form of a Helmholtz resonator or a short neck. The neck and the cavity of the Helmholtz resonator were intended to represent the sinus ostium and the paranasal sinus, respectively. The results show that AR-derived area-distance curves anterior to the sinus ostia are not affected by changes in ostium size or sinus volume; however, the cross-sectional areas posterior to the sinus ostia are significantly overestimated when ostium size or cavity volume is increased. Small ostia have little impact on AR measurements, regardless of sinus volume. Paranasal sinus volume can influence the area-distance curve beyond the ostium, but this effect is significant only when the sinus is connected to the nasal cavity by a relatively large opening.

AR measurements are reasonably accurate for diagnostic purposes only from the start of the acoustic pathway to the location of the sinus ostia. In other words, AR is only reliable for quantifying changes in the anterior part of nasal cavity. There are certain factors that cause overestimation and fluctuation of AR-derived cross-sectional areas posterior to the sinus ostia. The openings to the paranasal sinuses and the finite length of the nasal cavity significantly affect the area-distance curve in the posterior part of the cavity. On the basis of our experimental AR data for pipe models with a side branch and our theoretically calculated sound-power reflection coefficient, we conclude that AR does not provide accurate quantitative information about sinus ostium size, sinus volume, and changes in cross-sectional area of the nasal cavity posterior to the ostium. The overestimation of cross-sectional area beyond the sinus ostium is mainly due to loss of sound power through the open posterior end of the nasal cavity rather than loss through the ostia to the paranasal sinuses. However, it is important to note that the latter does have some influence. The oscillating pattern of the area-distance curve beyond the sinus ostium is associated with low-frequency acoustic resonances in that portion of the nasal cavity.

Our results also highlight that the algorithms used in AR omit the effects of the complex impedances of paranasal sinuses and sinus ostia and the low-frequency acoustic resonances in the nasal cavity posterior to the sinus ostium. As a consequence, the AR data beyond this location are open to misinterpretation, and, as noted above, the diagnostic value of this method is limited to the anterior part of the nasal cavity. It is important to be aware of these limitations to avoid misinterpreting AR data.

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