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Effects of the nasal valve on acoustic rhinometry measurements: a model study

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ACOUSTIC RHINOMETRY (AR) was introduced by Hilberg et al. (10) as an objective method for examining the nasal cavity. AR is a simple, noninvasive technique that has been widely accepted in a short period of time. It is potentially valuable for characterizing the geometry of the nasal cavity, quantifying the dimensions of nasal obstructions, and assessing results of surgery and response to medical treatment. However, certain factors inherent to the physics and algorithms involved in the technique limit the accuracy of AR. The most important limiting factor when quantifying the geometry of the anterior nasal cavity with AR is the passage area of the nasal valve. Thus, in assessing the accuracy of AR with respect to the complex nasal passage geometry, special attention must be paid to the influence of nasal valve passage area.

The precision of AR for estimating cross-sectional areas beyond a significant constriction is questionable. It has been suggested that the nasal valve may cause loss of energy from the incident sound wave, which would lead to underestimation of AR-measured area beyond the narrowed site (3, 9–11, 20). However, critical review of the literature reveals that the specific physical origin of the area underestimation and the reasons behind oscillations in the experimental area-distance curves posterior to the nasal valve are still not entirely clear. Furthermore, no attempts have been made to theoretically interpret the experimental AR data. Model studies supported by theoretical considerations are necessary if we are to understand the effects of the nasal valve on AR measurements.

The aim of this study was to investigate the influence of the nasal valve on area-distance curves recorded by use of commercially available AR equipment. To carry out the investigation, we used a simple nasal cavity model. This consisted of a metal pipe fitted with cylindrical inserts of various aperture diameters comparable to those of the human nasal valve. The experimental results are discussed in terms of theoretically calculated “sound-power transmission coefficients” and “sound-power reflection coefficients” for pipe model variations. Particular emphasis was placed on determining the reasons for area underestimation and for oscillations in the area-distance curves beyond the insert.

MATERIALS AND METHODS

A transient signal acoustic rhinometer (Ecco Vision, Hood Instruments, Pembroke, MA) was used to perform the acoustic measurements. The processed bandwidth for this particular rhinometer is in the frequency range 100 Hz to 10 kHz. To assess the influence of the nasal valve on the area-distance curve, a simple nasal cavity model was constructed from a brass pipe (12 cm long and 1.2 cm internal diameter) (Fig. 1). To simulate the nasal valve, a cylindrical insert of length \( l = 1.0 \) cm and inner diameter \( d \) was fitted inside the pipe. The models were identical except for the inner diameter and location of the insert, which constituted the two independent variables of the models used in this study. The inner diameters of the inserts ranged from \( d = 0.4 \) to 1.0 cm in 0.1-cm increments. The passage areas of the inserts were...
chosen in line with those of the actual human nasal valve (the mean passage areas in adults and 6-yr-old children are 0.60 cm² and 0.21 cm², respectively (4, 12, 22)) to imitate the normal anatomy and pathologies of this region. The experiments were repeated for pipe models in which the insert was placed at distances \( x_0 \) from the left (anterior) end of the pipe to the anterior end of the insert. \( S_1 \) and \( S_2 \) denote the cross-sectional areas of the main pipe and insert, respectively. The anterior end of the main pipe was connected to the nosepiece of the acoustic rhinometer.

The pipe models were designed such that there was secure contact between the model and the nosepiece of the rhinometer to prevent acoustic leakage. All AR measurements were repeated at least five times to ensure that the results were reproducible. The collected data were analyzed by use of Origin software (version 6.0, Microcal Software).

**EXPERIMENTAL RESULTS**

The results of AR measurements vary significantly depending on the inner diameter \( (d) \) of the insert and the distance \( (x_0) \) from the front edge (anterior opening) of the pipe to the insert. Figure 2, A and B, illustrates typical examples of the variation in experimental area-distance curves relative to inner diameter of the insert for pipe models with inserts located at \( x_0 = 2.0, 4.0, 6.0, \) and 8.0 cm from the beginning of the pipe. These distances were measured from where the nosepiece of the acoustic rhinometer was connected to the model.

The pipe models were designed such that there was secure contact between the model and the nosepiece of the rhinometer to prevent acoustic leakage. All AR measurements were repeated at least five times to ensure that the results were reproducible. The collected data were analyzed by use of Origin software (version 6.0, Microcal Software).

A striking feature of all the experimental AR data sets presented in Fig. 2 is that the cross-sectional areas...
Beyond the insert oscillate markedly. These oscillations are discernible even for the pipe model with an insert of the largest passage area $S_2 = 0.785 \text{ cm}^2$ (inner diameter $d = 1.0 \text{ cm}$). The amplitude of the oscillations tends to increase as the inner diameter of the insert is decreased from 1.0 to 0.4 cm (Fig. 2A). However, the location of the oscillation peaks, and hence the oscillation period (in units of length), seem to be independent of the inner diameter of the insert. Previous reports (1, 3, 9, 16) have noted similar oscillations in area-distance curves for pipe models with inserts simulating the nasal valve; however, none has provided a satisfactory theoretical explanation of this phenomenon.

The theory of sound-wave transmission through a pipe of finite length with an insert (i.e., constriction) provides some insight into the physical basis for underestimation of cross-sectional area beyond the constriction and for oscillations 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 expressions for sound-power reflection and transmission coefficients for the pipe models used in this study. This theory is an integral component of our interpretation and discussion of the experimental data; hence, it is briefly outlined in the next section. Then we discuss the experimental results in this theoretical framework.

**THEORY AND NUMERICAL RESULTS**

In this study, we consider the propagation of plane acoustic waves through a mechanical system produced by inserting a constricted section of pipe of cross-sectional area $S_2$ and length $l$ in a pipe of cross-sectional area $S_1$, as shown in Fig. 1. The presence of a constriction causes the acoustic impedance at the junction to differ from $Z_1 = \rho_0 c / S_1$, the characteristic impedance for plane waves in a long pipe of cross-sectional area $S_1$ (here $\rho_0 = 1.21 \times 10^{-3} \text{ g/cm}^2$ and $c = 34,300 \text{ cm/s}$ are the density of air and sound velocity in air, respectively), and consequently a reflected wave is produced (8, 17). This leads to a reduction in the acoustic energy that is transmitted through the section of pipe beyond the constriction. In the following analysis of the propagation of plane acoustic waves through the model system (Fig. 1), it is assumed that the cross-sectional dimensions of all pipes are small relative to the sound wavelength ($\lambda$). This assumption is valid for all pipe models examined in the present work, because the shortest wavelength produced by the AR instrument is ~3.43 cm.

The sound-power transmission coefficient for the model system shown in Fig. 1 can be calculated by considering the incident, reflected, and transmitted waves present in the three sections of the model. The sound waves in these sections are related to each other by the usual conditions of continuity of pressure and continuity of volume velocity at the two junctions of the constricted pipe (the beginning and end of the insert) with the main pipe. In the steady state, the rate at which acoustic energy is reflected back into the pipe anterior to the constriction plus the rate at which it is transmitted into the pipe posterior to the constriction is equal to the rate of arrival of the incident energy. When the pipe beyond the constriction is either of infinite length or terminated such that no reflected wave is returned from its far end to set up standing waves, the sound-power transmission coefficient ($\alpha_t$) from the anterior pipe through the constriction into the posterior pipe is given by the equation (17)

$$\alpha_t = \frac{4}{4 \cos^2 k l + \left( \frac{S_2}{S_1} + \frac{S_1}{S_2} \right) \sin^2 k l}$$

where $k (=2\pi/\lambda)$ is the wavelength constant. The sound-power reflection coefficient ($\alpha_r$) is defined by

$$\alpha_r = 1 - \alpha_t$$

The frequency dependence of the sound-power transmission and reflection coefficients, as calculated using Eqs. 1 and 2, are shown in Fig. 3. The presence of a constriction affected the homogeneity of the frequency spectrum of the transmitted wave, because the effective acoustic impedance of the model system is frequency dependent. For models with an insert of small inner diameter (small passage area), the transmission coefficient decreases substantially with increasing frequency. The high-frequency components of the acoustic pulse generated by AR do not reach the portion of the main pipe beyond the constriction, because these waves are reflected back from the barrier created by the junction at the start of the insert. This is important, because the transmitted sound waves probe and hence provide information about the cross-sectional area of the portion of the main pipe beyond the constriction. These results imply that relatively higher degrees of error should be expected when measuring the cross-sectional area beyond a constriction of small passage area. Because AR measures the intensity of reflected sound waves and compares this with the intensity of incident waves, one would expect the mea-

![Fig. 3. Frequency dependence of sound-power transmission (solid lines, labeled by T1, T2, and T3) and reflection (dashed lines, labeled by R1, R2, and R3) coefficients for models with a main pipe of infinite length.](http://www.jap.org)
sured cross-sectional areas beyond the insert to be lower than the true cross-sectional area $S_1$.

In the more general case, in which the main pipe beyond the constriction is of finite length and is terminated in an impedance $Z_L$, the input impedance $Z_3$ of the continuing pipe is given by the equation (8, 17)

$$Z_3 = \frac{\rho_0 c}{S_1} Z$$

with

$$Z = \frac{Z_L + j\frac{\rho_0 c}{S_1} \tan kL}{\frac{\rho_0 c}{S_1} + jZ_L \tan kL}$$

where $j = (-1)^{1/2}$. The acoustic impedance $Z_3$ in the transmitted wave depends on the terminating impedance $Z_L$, the length $L$ of the pipe beyond the constriction, and the wavelength constant $k$. At low frequencies, where $2ka < 0.5$ (a condition that is satisfied to a large extent for all the pipe models used in this study), the terminal acoustic impedance of an unflanged, open-ended pipe is approximately equal to (17)

$$Z_L = \frac{\rho_0 c}{S_1} \left(\frac{k^2 a^2}{4} + j(0.6ka)\right)$$

where $a$ is the radius of the main pipe (see Fig. 1). Hence, the sound-power transmission coefficient ($\alpha_t$) from the anterior pipe through the constriction into the posterior pipe can be approximated by

$$\alpha_t = \frac{4|Z|}{(|Z| + 1)^2 \cos^2 kl + \left(\frac{S_2}{S_1} Z + \frac{S_1}{S_2} \right)^2 \sin^2 kl}$$

For $|Z| = 1$, Eq. 6 reduces to Eq. 1, as would be expected.

Because the length of pipe beyond the constriction is finite, 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 constriction. It can be shown that the resonant frequencies ($f_n$) of an open-ended, unflanged pipe of length $L$ are given by

$$f_n = \frac{c}{2(L + 0.6a)} \quad n = 1, 2, 3, \ldots$$

The resonant frequencies of the portion of the main pipe beyond the constriction were calculated using Eq. 7 with $c = 34,300$ cm/s, $L = 9$ cm, and $a = 0.6$ cm. For this particular configuration, the fundamental (1,832 Hz), first (3,664 Hz), second (5,496 Hz), third (7,328 Hz), and fourth (9,160 Hz) harmonics fall within the frequency bandwidth of the AR instrument. The fifth overtone (10,992 Hz) is just at the upper border or slightly out of the range, and the sixth overtone (12,824 Hz) is well out of the range. Whenever the incident sound wave has a component that corresponds to the resonant frequency $f_n$ of the main pipe beyond the constriction, its input impedance $Z_3$ attains a minimum and the sound power radiated out of its open end becomes a maximum for a source of constant pressure amplitude (17). If the sound frequency does not match one of the resonant frequencies, only a small percentage of the incident acoustic power is transmitted out of the pipe, the remainder being reflected back down the pipe. As a consequence, one would expect consecutive minima and maxima to appear in the plots of both sound-power transmission and reflection coefficients vs. sound frequency.

By combining Eqs. 3-6, we calculated the sound-power reflection coefficient $\alpha_r = (1 - \alpha_t)$ as a function of sound frequency for selected inner diameter values of the insert. The results are shown in Fig. 4, which, for clarity, shows only the data sets for three different inner diameters. For models with a constriction and main pipe of finite length, the sound-power reflection coefficient exhibits pronounced oscillations when the sound frequency is increased from 100 Hz to 10 kHz. As a consequence, the measured cross-sectional areas beyond the insert would be expected to oscillate, because AR measures the intensity of reflected sound waves relative to that of incident waves. The oscillatory behavior of the sound-power reflection coefficient with frequency and the oscillations in the experimental area-distance curves measured by AR are closely related to each other; hence, the latter are mainly governed by the acoustic resonances in the portion of the main pipe beyond the constriction.

To demonstrate this correlation between the oscillations of experimental area-distance curves and those of the sound-power reflection coefficient more clearly, we calculated the frequency average of the sound-power reflection coefficient $[\alpha_{r,m}(x)]$, defined by (3)

$$\alpha_{r,m}(x) = \frac{1}{9,900} \int_{100}^{10,000} \alpha_r(x, f)df$$

Here $x$ is the distance measured from the end of the insert. Figure 5, A and B, compares the experimental

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**Fig. 4. Frequency dependence of sound-power reflection coefficient for models with a main pipe of finite length. The 3 plots represent 3 different insert diameters, as shown inside the graph.**
The anatomy of the human nose is complex, and the nasal valve is the narrowest section of this structure. The nasal valve is also the most important part of the nasal passage with respect to respiratory physiology. The precision of AR measurements in the anterior part of the nose, which contains the nasal valve, is very significant in terms of the value of this method in rhinology. Ever since acoustic pulse-response analysis

\[ P_3 = [(A_3 + B_3)^2 \cos^2 (kx + \theta/2) + (A_3 - B_3)^2 \sin^2 (kx + \theta/2)]^{1/2} \] (9)

Here, \( A_3 \) and \( B_3 \) represent the magnitude of the complex amplitude of the wave transmitted into the pipe beyond the constriction and that of the reflected wave at the open end of the pipe, respectively. The phase angle \( \theta \) is a measure of the amount by which the reflected pressure at the open end of the main pipe leads or lags behind the incident pressure. According to Eq. 9, for sound waves of a given frequency, pressure antinodes of amplitude \( A_3 + B_3 \) occur at coordinate positions where \( \cos^2 (kx + \theta/2) = 1 \), and pressure nodes of amplitude \( A_3 - B_3 \) correspondingly occur at places where \( \sin^2 (kx + \theta/2) = 1 \). Hence, irrespective of the value of \( \theta \), the distance between two consecutive pressure antinodes (nodes) is equal to \( \lambda/2 \). The experimental area-distance curves obtained for our pipe models exhibit relative maxima every 11–12 data points (see Fig 2A). The AR instrument produces a data point every 0.24 cm, implying that \( \lambda \approx 5.76 \) cm, which corresponds to a frequency of 5,955 Hz (roughly equal to that of the second overtone). A comparison between the frequency average of standing-wave amplitude and the experimental area-distance curve, obtained for the model with an insert of inner diameter \( d = 1.0 \) cm, is shown in Fig 6. Apart from the apparent phase shift, there is one-to-one correspondence between the oscillations in the AR-determined area-distance curve and those in the calculated frequency average of standing-wave amplitude. These findings provide further support to the suggestion that the oscillations observed in the experimental area-distance curves are due to low-frequency acoustic resonances in the portion of the main pipe beyond the constriction.

DISCUSSION

The formation of a reflected wave at the open end of the main pipe generates a complicated pattern of standing waves in the section of pipe beyond the insert. However, because the incident sound pulse produced by AR 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. For a plane sound wave of angular frequency \( \omega = 2\pi f = ck \), the amplitude \( P_3 \) of the standing wave in the portion of the main pipe beyond the constriction is given by (17)

\[ P_3 = [(A_3 + B_3)^2 \cos^2 (kx + \theta/2) + (A_3 - B_3)^2 \sin^2 (kx + \theta/2)]^{1/2} \] (9)

The formation of a reflected wave at the open end of the main pipe generates a complicated pattern of standing waves in the section of pipe beyond the insert. However, because the incident sound pulse produced by AR 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. For a plane sound wave of angular frequency \( \omega = 2\pi f = ck \), the amplitude \( P_3 \) of the standing wave in the portion of the main pipe beyond the constriction is given by (17)
was first described (19), precise quantification of cross-sectional areas distal to a narrow aperture has been the most widely recognized problem (3, 9–12, 20). While considering the accuracy of nasal cavity measurements obtained by AR, it is important to assess how the nasal valve influences the area-distance curves determined by this method. The reason is that this constriction introduces errors in the measurement of cross-sectional areas in the posterior nasal cavity.

In a previous work (3), we investigated the factors that affect the accuracy of AR measurements, with special focus on the nasal valve region. As in the present study, the simple models we used consisted of a metal pipe with cylindrical inserts of various lengths and diameters that were comparable to the dimensions of the human nasal valve. The earlier data revealed that the passage area of the insert was consistently overestimated. Also, the probability of measurement errors was higher when the passage area and the length of the insert were small and short, respectively.

The area underestimation that occurs with AR beyond this initial constriction of nasal cavity has been attributed to viscous forces (10), transmission losses (1), and internal losses (20) in the nasal valve. However, it can be readily shown by simple calculations that the sound-power losses due to viscosity forces in air are negligible in a pipe of radius exceeding 1 mm (8, 17). Recently, Hilberg and Pedersen (12) proposed guidelines for optimal application of acoustic rhinometry and presented experimental area-distance curves for a “standard nose” model and a step model. The nasal valve area of the standard nose was 0.45 cm², which corresponds to an inner diameter of 0.76 cm, and the true cross-sectional area of the standard nose posterior to the nasal valve increased gradually with increasing distance. They found good agreement between the AR-determined cross-sectional areas and the true areas of the standard nose; however, the accuracy decreased as the distance from the beginning of the model was increased. Furthermore, Hilberg and Pedersen demonstrated that AR underestimates the cross-sectional areas of the step model, which had a nasal valve area of 0.38 cm² (inner diameter = 0.695 cm), and the corresponding area-distance curves showed marked oscillations. They concluded that steep changes cause underestimation of the area. The results of our present study on simple nasal cavity models confirm that AR underestimates the cross-sectional area beyond an insert of inner diameter \( d \leq 0.6 \) cm (passage area \( S_2 \leq 0.28 \text{ cm}^2 \)) and that the degree of this area underestimation decreases as \( d \) is increased above 0.6 cm (Fig. 2). On the basis of this experimental finding, one would expect that any area underestimation for the standard nose used by Hilberg and Pedersen to be negligibly small, because it had a relatively larger passage area.

The area underestimation and oscillations in the area-distance curves derived by AR can be understood by examining the theory of propagation of plane acoustic waves through a finite pipe with a constriction simulating the nasal valve. Our theoretical results for the sound-power transmission coefficient indicate that, when the passage area of the constriction is small, most components of the acoustic pulse generated by AR do not reach the section of pipe beyond the constriction. Only a small portion of the incident sound power is transmitted through the constriction. This means that the area underestimation beyond the constriction is due to the reflection of most of the incident sound power from the barrier at the front junction between the main pipe and the constriction. A similar interpretation may apply to the human nasal cavity, with its initial constriction (the nasal valve) and its acoustic pathway of finite length.

The experimental AR curves for all the pipe models used in this study showed pronounced oscillation beyond the insert. Although the oscillation amplitude varies significantly depending on the inner diameter of the insert, the oscillation period (in units of length) is roughly constant and independent of insert dimensions. Oscillations in area-distance curves have also been reported by several other researchers (1, 3, 9) who have studied pipe models with an insert of similar dimensions. Buenting et al. (1) argued that these fluctuations must originate either in the mathematical deconvolution of the digitized signal or in low-frequency acoustic resonance, but they offered no satisfactory theoretical explanation. As demonstrated in the previous section of this paper, the oscillating pattern we observed originates mainly from low-frequency acoustic resonances in the portion of the main pipe beyond the insert. In line with this, one would expect the sound-power reflection coefficient of the nasal cavity to oscillate as a function of sound frequency and as a function of distance. Recently, Cakmak et al. (2) observed oscillations in the area-distance curves determined by AR for pipe models with Helmholtz resonator as a side branch, which simulated the sinus ostium and paranasal sinus. They proved that the oscillations are due to low-frequency acoustic resonances in the portion of the pipe beyond the side branch.

![Fig. 6. Comparison of AR-determined area-distance curve (●) and the frequency average of the amplitude of standing wave generated in the portion of the main pipe beyond the insert (dotted line). Both the experimental and calculated data correspond to a pipe model with an insert of inner diameter \( d = 1.0 \) cm.](image-url)
It should be noted that the acoustic impedance of nasal cavity beyond the nasal valve is complex and can be approximated by Eq. 3 above, not by \( Z(x) = \rho c S(x) \), as assumed in the algorithms used in AR (14, 15). The results of the model calculations we have presented in this study and in a previous study (2) suggest a need for further improvement in the design of AR equipment and related computer software (6, 13–15). The complex impedance and finite length of the nasal cavity (and, hence, the corresponding low-frequency acoustic resonances) must be considered in the AR algorithms.

Diagnostically, AR measurements of the anterior nasal passage are reasonably accurate if the passage area of the nasal valve is within normal ranges. However, the pathologies narrowing the anterior nasal passage such as septal deviations, polyps, tumors, webs, strictures, or the nasal valve of the pediatric population may significantly affect the AR measurements, when equipment intended for adults is used. In clinical studies, oscillation of the area-distance curve beyond the significant constriction may lead to misinterpretation. Also, investigation of the literature shows that several reports have presented artifacts associated with AR technique as valid data (5, 7, 18, 21). It is very important that all users of AR be aware of the potential sources of errors we have exposed in this study. Also, clear definitions of the components of the AR trace are needed (12). It is important to be aware of the limitations of this method, as this is the only way to avoid misinterpreting AR measurements.

In conclusion, the anatomy of the human nose is complex, and the spectrum of individual differences is broad. The accuracy of AR measurements of the nasal cavity depends greatly on nasal passage anatomy, especially that of the narrowest section. AR measurements of the anterior nasal passage are reasonably accurate if the nasal valve area is within normal ranges. AR underestimates cross-sectional area beyond a significant constriction, and the corresponding area-distance curves show pronounced oscillations. Our results suggest that AR is only reliable for quantifying changes of the initial portion of the nasal cavity, anterior to significant constrictions such as pathologies narrowing the nasal valve. The decrease in the passage area of the nasal valve lessens the role of AR as a diagnostic tool for measuring the entire nasal cavity.

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