Acoustic rhinometry: validation by three-dimensionally reconstructed computer tomographic scans

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Terheyden, Hendrik, Steffen Maune, Jürgen Mertens, and Ole Hilberg. Acoustic rhinometry: validation by three-dimensionally reconstructed computer tomographic scans. J Appl Physiol 89: 1013–1021, 2000.—The aim of the present study was a validation of acoustic rhinometry (AR) by computed tomography (CT). Six healthy subjects were examined by CT and AR. The CT data were processed in a computer program (AutoCAD), and a virtual three-dimensional model of each nasal cavity was constructed. This model permitted an individual prediction of the center line of the sound wave propagation through the air volume of the nasal cavity with the cross-sectional areas oriented perpendicularly to this line. The area-distance curves derived from AR and CT were compared. Linear regression analysis revealed a reasonable agreement of AR and CT in the anterior nose below a mean of 6 cm distance from the nostrils \( r = 0.839, P < 0.01, m = 1.123, b = -0.113 \) (AR \( = m \times CT + b \)). The measuring accuracy using CT as gold standard revealed a mean error at the nasal valve of \( <0.01 \text{ cm}^2 \) (4.52%) and at the nasal isthmus of \( 0.02 \text{ cm}^2 \) (1.87%). Beyond 6 cm, the correlation decreased \( (r = 0.419) \), and overestimation of the true area occurred (100%). In conclusion, the measurements were reasonably accurate for diagnostic use up to the turbinate head region. Certain factors induce an overestimation of the true areas beyond this region. However, these factors are constant and reproducible in a single subject, and intraindividual comparative measurements are possible beyond the turbinate head region.

virtual model; nasal isthmus; nose anatomy; acoustic reflections; airway cross-sectional areas; computed tomography

ACOUSTIC REFLECTIONS HAVE been used to make in vivo cross-sectional measurements of the human trachea and the lower airways (8, 19). In 1989, the method was introduced for assessment of the patency of the nose, called acoustic rhinometry (AR) (15). Briefly, AR is based on reflections of an acoustic pulse applied to the nostrils. From the reflected wave, the serial distribution of impedance can be calculated as a function of traveling time. Because acoustic impedance depends on the cross-sectional area, the result is presented as a serial distribution of cross sections of an acoustic system equivalent to the acoustic properties of the nose (19). The method is noninvasive, requires little cooperation of the subject, and is even applicable in small children (2).

It was demonstrated in clinical studies that AR is a sensitive and reproducible method to detect relative changes in the dimensions of the nasal cavity (15, 16). Intraindividually, reactions of the erectile nasal mucosa due to posture (7), topical decongestants (12), vascular reaction to skin cooling (30), and allergic challenge (63) could be monitored. The method was reported to be sensitive to relative intraindividual changes after operations on the septum (11) and the turbinates (14), adenoidectomies (6), or growing masses of the nasal cavity (25).

However, it has been difficult to clinically correlate the area-distance function of AR with certain anatomic structures of the nasal cavity. The two anterior notches of the area-distance curve were related to the nasal valve and the head of the anterior turbinate on the basis of clinical experience from decongestion studies (11). Beyond these points, anatomical correlations were based on distances from the nospiece of the rhinometer on a straight line.

Numerous attempts were made to validate AR by correlation with an area-distance curve derived from other methods (2, 3, 13, 15, 16, 24, 27, 28). Experiments employed tube airway models (2, 12), anatomic models derived from casts (24), or stereolithography (16). However, neither models nor cadaver studies (15, 27) reproduce the acoustic properties of the vital nasal mucosa (15). Consequently, in vivo data of human subjects were required. A first attempt was made with the water displacement method (15). In vivo validation experiments obtained area-distance curves from computed tomography (CT) and magnetic resonance imaging (MRI) (3, 10, 16, 28). However, in these studies, serial parallel measuring planes placed arbitrarily in the nose at uniform distances on a straight line from the nostril to the pharynx (3, 10, 28) or slightly indi...
individualized planes (16) were applied. This was probably an undue simplification, and most authors speculated that mismatching of the area-distance curves and overestimation in the posterior nose might be due to a difference in the axis of the AR measuring planes and the scans (16, 28, 30). Obviously, the nasal airway is curved, and anatomic structures such as turbinates act as obstacles in the direct line from the nosepiece to the pharynx (15). Thus it is problematic to correlate area-distance curves derived from other methods with those derived by AR, unless the individual sound path and the individual measuring planes were known. No study has been reported yet either using individualized measuring planes or correlating the very first part of the nasal airway, the isthmus and valve region, with CT or MRI data.

Hence, the aim of the present study was to correlate in vivo acoustic data of human subjects with CT data, using individual measuring planes. The individual measuring planes were determined in a virtual three-dimensional model of the nasal airways based on the CT data.

METHODS

Subjects. Thirty adult patients, who were referred to a radiological center for a CT of the nose and paranasal sinuses for various reasons, were examined. From the total of 30 patients, the data of six patients without visible pathologic changes, three men and three women, finally were included in this study.

Equipment. The CT examinations were performed on a EXEL-2400-elite scanner (Elscint, Wiesbaden, Germany) in axial sections of 2.5-mm thickness at 2-mm table increment. The following parameters were used: 120 Kv, 252 mAs, and 2.1-s scan time. Window width was 2,000 Hounsfield units, and the window was centered at 200 Hounsfield units. Obviously, the nasal airway is curved, and anatomic structures such as turbinates act as obstacles in the direct line from the nosepiece to the pharynx (15). Thus it is problematic to correlate area-distance curves derived from other methods with those derived by AR, unless the individual sound path and the individual measuring planes were known. No study has been reported yet either using individualized measuring planes or correlating the very first part of the nasal airway, the isthmus and valve region, with CT or MRI data.

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A single-impulse rhinometer (Rhinoklack RK 1000, Stimotron, Wendelstein, Germany) was used. Although AR has been described in detail, the principle shall briefly be reviewed here. An audible sound impulse containing a homogenous frequency spectrum from 0 to 20 kHz is produced by a spark discharge. The impulse propagates down a wave tube. It passes the microphone and enters the nasal cavity via a 7-cm-long acrylic nose piece. The sound is reflected by changes in the local impedance. The reflected wave is recorded by a piezoelectric microphone, low-pass filtered at a cutoff frequency of 10 kHz, high-pass filtered at 150 Hz, and amplified by 20 dB. The signal is digitized at a sampling rate of 50 kHz in a 12-bit analog-to-digital converter. As described by Jackson and co-workers (19), the impulse response h(t) is computed by comparing the incident and reflected acoustic pressure waves by inverse fast Fourier transform. A serial sequence of local characteristic impedance z(t) can be recovered from the impulse response using the Ware and Aki algorithm (19). Because the local characteristic impedance z is a function of traveling time, it is possible to calculate from z(t) the shape of an equivalent geometric system, given by an area-distance function A(x) = p_o e^ct, where p_o is the density of the gas and c is the velocity of wave propagation (19).

Data acquisition. To exclude climatic influence or the influence of posture or the physiological nasal cycle on the erectile parts of the nasal mucosa, the examinations were carried out under nasal decongestion with two sprays of 640 µg xylometazoline to each nostril 30 min before the examination. Immediately after the CT, the patients changed to a sitting position. In the same room, AR was performed without delay. Tight fit of the nasal applicator without sound leaks was achieved by individualization with cotton and tape.

Virtual three-dimensional model of nasal air spaces. The segmentation of the axial CT scans was performed semiautomatically based on the difference in gray levels of air and mucosa. The automatic segmentation was supplemented by a single radiologist for anatomical and clinical plausibility and corrected if necessary. The outlines of these segmented nasal air spaces were transferred manually by a digitizing tablet using a cross-hair cursor into two-dimensional vector graphics in a personal computer. The theoretical accuracy of this transfer is 0.02 mm. In a computer program (AutoCAD version 11.0, Autodesk, San Rafael, CA), the two-dimensional layers were combined to form a three-dimensional virtual model of the nasal air space. In this model, cross sections could be obtained in any desired position and angle.

Refraction of waves follows Huygen’s principle: every point of a wave front is the origin of a new spherical wave (4). In AR, the acoustic waves travel through the nose down into the pharynx and are refracted according to the curvature of the upper airways and anatomical structures in the nose. The sound energy is transported by air and therefore limited to the air-filled volume of the nose. According to Huygen’s principle, the sound impulse from the nasal applicator is dispersed inside the nose in numerous single impulses. These single impulses travel in the air volume and undergo multiple reflections from the walls. They form an average wave front that travels along the centerline of the nasal air-filled volume.

The aim of the study was to compare a CT-derived area-distance curve of the subject with the acoustically derived area-distance curve. An area-distance curve is the serial distribution of cross-sectional areas perpendicularly oriented to the individual center line of the nasal air volume. The individual area-distance curve was obtained by a twofold iterative mathematical approximation. First, an approximated center line was placed into the lateral aspect of the nasal air volume (z-axis of the nose). This line consisted of three straight parts from the anterior to the posterior nose. The first part of the line started anteriorly in line with the nasal applicator −45° from the line of gravity. In the region of the turbinate heads, a 45° bend put the second part of the line horizontal to the line of gravity parallel to the nasal floor. Beyond the choanae, the third part of the line descended 45° from the line of gravity and entered the epipharynx and the beginning of the pharyngeal curvature. Perpendicularly along this line, the nasal air volume was cut subsequently every 3.33 mm to the approximated centerline to measure the cross-sectional areas in the frontal aspect (x, y-axis). The procedure was then repeated, now based on an individual center line. The cross-sectional areas based on the approximated center line were depicted. It was possible for the computer program to calculate the center points (centers of gravity) of such a two-dimensional cross-sectional area on each nasal side. These mathematically derived center points of the cross sections were connected subsequently by a line from anterior to posterior in the nose. The aligned center points then formed a center line of the nasal air volume, which was individualized in all three dimensions (x, y, and z) (Figs. 1 and 2). Cross-sectional areas of the virtual model of the nasal airway were calculated perpendicularly to this.
addition is required because of an inherent attenuation in AR. Every change in the actual cross-sectional area of the acoustic conductor is depicted in the acoustically derived area-distance curve about three points (~10 mm) behind the true position of the change (2, 17, 19).

**Statistical analysis.** The acoustic curve was subtracted from the CT curve, and the absolute and percentage error of measurement were calculated as a function of distance from the nostrils.

Second, linear regression and correlation analysis were performed. For each analysis, it was ensured that the two data sets, acoustic and CT, were approximately normally distributed. The correlation coefficient was calculated and checked with Fisher’s $z$-transformation at a significance level of 0.05. Three regression analyses were performed. 1) For each of the 12 nasal cavities, acoustic and CT-derived areas for all distances were compared by linear regression analysis, and the mean of the 12 regression analyses was calculated. 2) The same type of analysis was applied to the data of the anterior part of the nose, a subgroup of the data of the first analysis. The anterior part was defined for distances <6 cm and represented anatomically the nasal valve and the anterior part of the inferior turbinate. 3) The same type of anal-
ysis was applied to the data of the posterior part of the nose, a subgroup of the data of the first analysis. The posterior part was defined for distances >6 cm and represented the posterior part of the turbinates, the choanae, and the epipharynx.

Spatial accuracy was examined by subtracting the AR-derived distances from those derived by CT at the second minimum (isthmus nasi) and at the maximum of the curves (epipharynx).

RESULTS

Regression and correlation analysis. Table 1 reviews the results of the intraindividual measurements evaluated by linear regression. The mean values for the 12 regression lines for each of the 12 cavities (means of slope, intercept, correlation coefficients and degrees of significance) were calculated.

In the data of the entire scan, a moderate correlation of \( r = 0.684 \) was observed. Two of the cases did not reach significance. When the plain curves were compared (Fig. 3), a higher degree of identity was observed in the anterior than in the posterior part. Thus a partition of the curves was performed after 6 cm, and both parts were analyzed separately. With \( r = 0.839 \) and significance in all 12 cases, the correlation in the anterior part was higher than in the entire scan. The regression line with the function \( f(CT) = 1.123 \text{AR} - 0.113 \) (where CT and AR are the cross-sectional areas measured by CT and AR, respectively) was not far from identity. In the posterior part, the correlation coefficient was \( r = 0.419 \), considerably lower than in the anterior region and in the entire scan. In four cases,
significance levels were not achieved, or negative trends were even detected. In a few cases (Fig. 3, I and J), a reverse correlation in the posterior part due to divergent curves was observed. These cases had a negative impact on the mean correlation coefficients. Absolute and percentage error of measurement. The mean error of measurement was $0.01 \text{ cm}^2 (4.52\%)$ in the nasal valve region and $0.02 \text{ cm}^2 (-1.87\%)$ in the isthmus region (Table 2). Between the first and second anterior notch of the acoustic curve, the mean area was underestimated by 16.9%. Beginning at the region of the middle of the turbinates, the error of measurement increased up to $2.03 \text{ cm}^2$ in the region of the choanae. In the epipharynx, the error further inclined up to $2.70 \text{ cm}^2$. The error in the posterior part exceeded 100%. However, a look at the plain curves (Fig. 3) shows that after ~6 cm the curves are divergent but follow a comparable pattern. The maximum of the epipharynx could be identified in all curves. Figure 4 shows that, in the posterior part, the acoustic measurement overestimates the true areas, indicating a systematic error.

Spatial resolution. The error of spatial measurement was examined by comparing the AR- and CT-derived curves at the positions of the second minimum (notch) and the maximum. The second minimum was measured by AR at a mean distance of 2.27 cm from the nostril and by CT at 2.07 cm. The mean error of measurement was 0.2 cm (2.13%). The maximum of the acoustic curves was observed at 10.20 cm and of the CT curves at 9.78 cm. The mean difference was 0.42 cm (2.48%).

**DISCUSSION**

The measuring accuracy of AR was investigated in six human subjects (12 nasal cavities). Individually
defined cross sections of a virtual three-dimensional model of the airways based on CT data were used as a gold standard. In the nasal valve and the nasal isthmus, the measuring accuracy was high, with 4.52% (<0.01 cm²) and 1.87% (0.02 cm²) measurement error, respectively, and a correlation analysis close to identity. Starting in the middle of the turbinate region, the measuring accuracy was high, with 4.52% (0.01 cm²) and 1.87% (0.02 cm²) measurement error, respectively, and a correlation analysis close to identity.

In the virtual model of the nasal air space, the nostrils applied afterward to the nostrils for AR examination. Because this difference is below the spatial resolution of AR, this small inaccuracy is not expected to cause great differences in the measured areas. In AR, the position of a rapid area change in an acoustic conductor may display 8–10 mm behind the true position known from tube model studies, because of an inherent attenuation in the acoustic system (2, 17, 19). Thus the true position of the nasal isthmus is not at the notch but where the curve initially starts to deflect. We aligned both area-distance curves, adding 10 mm to the distance to the CT-derived area-distance curve, as was done by others before (30). This approach was justified by the high accuracy of spatial measurement in the present data. The CT scans were made with the nosepiece not in place. The nosepiece was applied afterward to the nostrils for AR examination.

In the present study, the three-dimensional orientation of the individual measuring planes has been determined mathematically on the basis of clinical evidence and conformity to physical laws of propagation of sound waves. Because of the complexity of three-dimensional sound wave propagation and the complex anatomy of the nasal cavity, on the other hand, the correctness of this theoretical model cannot be proven experimentally. The individual sound path predicted by mathematical methods in the present study was very similar to that described by Hilberg and co-workers in a water displacement study (15). In the anterior nose the axis is ascending. Above the head of the inferior turbinate, the axis bends relatively sharply, descends, and leads finally into the pharynx. In all three dimensions, the individual axis deviates from a straight line from the nosepiece to the pharynx. Thus distances measured in straight lines from the nosepiece as used in some previous validation studies are questionable (3, 10, 16, 28). This includes measurement of the nasal volume by simple integration of the area-distance curve, because the cross sections measured are not parallel to one another and thus are not unique volume segments (22).

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In the virtual model of the nasal air space, the nostrils were discernible and were used as the start point for the measured distances of the CT-derived area-distance curve. This procedure did not cause an inaccuracy greater than a few millimeters, as shown by the good matching of both area-distance curves in terms of spatial measurement of certain anatomic landmarks. Because this difference is below the spatial resolution of AR, this small inaccuracy is not expected to cause great differences in the measured areas.

In a CT study using nonindividualized measuring planes, a low correlation coefficient of 0.23 before the

<table>
<thead>
<tr>
<th>Distance from nostril, cm</th>
<th>Valve</th>
<th>Isthmus</th>
<th>Middle Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–1</td>
<td>1–2</td>
<td>2–3</td>
</tr>
<tr>
<td>Error, cm²</td>
<td>&lt;0.01 ± 0.16</td>
<td>−0.18 ± 0.18</td>
<td>−0.02 ± 0.24</td>
</tr>
<tr>
<td>Error, %</td>
<td>4.52 ± 22.30</td>
<td>−16.90 ± 20.22</td>
<td>−1.87 ± 18.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distance from nostril, cm</th>
<th>Choana</th>
<th>Epipharynx 7–8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7–8</td>
<td>8–9</td>
</tr>
<tr>
<td>Error, cm²</td>
<td>2.03 ± 0.99</td>
<td>2.41 ± 1.51</td>
</tr>
<tr>
<td>Error, %</td>
<td>117.9 ± 67.86</td>
<td>120.3 ± 86.92</td>
</tr>
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</table>

Values are means ± SD.
second notch of the acoustic area-distance curve and 0.13 behind the second notch was observed (28). In a similar experiment comparing the areas at the notches with CT, correlation coefficients of 0.92 at the first-notch and 0.56 at the second notch were calculated (10). The respective values of the present study would be 0.950 and 0.697 (not included in RESULTS, because another type of analysis was applied). In the trachea, a high correlation with CT \((r = 0.91)\) and error of measurement between 7 and 9\% was observed (5). In a MRI study using a different type of data analysis than the present study (nonindividualized measuring planes), a correlation coefficient of 0.959 was found in the anterior part of the nose after decongestion (3). In a MRI study using a similar type of data management as in the present study, the mean correlation coefficient for the entire scan was 0.782 vs. 0.684 in the present study (15). In the posterior part of the nose, in the present study the correlation was lower (0.419) compared with the MRI study (0.585) (15). However, in the present study a higher correlation was observed in the anterior part of the nose, 0.839 vs. 0.730 in the MRI study (15). The most anterior parts of the nose were omitted in that MRI study, and no individualized measuring planes were obtained in that area (15). In the present study, the anterior parts of the nose could be included. These measurements document the accuracy of AR in the clinically important regions of the nasal valve and the turbinate head. This measuring accuracy and the values observed for the anterior part in the present study are within the variation range (5–10\%) of the acoustic reflection measurements described for the nose (17) and the trachea (1). The use of individualized measuring planes in the present study led to a higher agreement of AR and CT data compared with other studies in the anterior part of the nose (3, 10, 28). However, in the epipharynx, a significant error of measurement was demonstrated although individualized measuring planes were used.

A surplus of area compared with the CT curves was observed in all AR curves for distances greater than a mean of 6 cm. The constant overestimation suggests systematic errors rather than random errors. Any internal loss of sound energy would result in a reduction in the amplitude of the reflected wave, which in turn would result in an underestimate of changes in area with growing distance (20). Thus, in a system such as the nose in which the area decreases after a maximum in the middle turbinate region, the area of a constriction more distant from the nosepiece would be overestimated (15). The wave would be attenuated with distance traveled. Internal losses have not been measured yet and are difficult to measure (20). Because the magnitude of internal losses is not known, their effects cannot be predicted at a given distance. When the source of surplus area or sound loss was sought, on the other hand, different influences have been discussed. Generally speaking, all contributing factors may be violations of the physical idealizations inherent in the acoustic method in vivo (5, 17, 18). The idealizations inherent in the application of the acoustic technique in vivo can be divided into two categories, concerning the physical behavior of the examined structures and the computational methods (5, 21). The first category includes symmetric branching, plane wave fronts, rigid walls without viscous losses, lack of internal losses due to gas viscosity, constant gas composition, temperature, and humidity (5). The second category includes infinite computational accuracy and zero discretization error (5). These factors have been extensively discussed for reflection measurements of the lower airways (5). The idealizations are also violated in the nose to a certain extent (17).

Symmetric branching is an idealization in the acoustic reflection technique (19). If the acoustic conductor branches asymmetrically, it is impossible to separate the contribution of both sides. Such an asymmetrical branching is encountered at the distal end of the septum, where the contralateral nasal cavity opens. Here parts of the incident sound wave are lost to analysis. The contribution of the contralateral side was experimentally shown in tube models (21, 23) and seems to be of minor importance (18). The openings of paranasal sinuses are sources of sound loss and significantly affected the area-distance function in the posterior part (18). In that study, employing a tube model, a stereolithographic model, and magnetic resonance tomographies in humans, deviation between the acoustic and true curves at a depth of 6.1 cm in the nose were observed (18). This value is confirmed in the present study, in which deviations started at 6 cm (Fig. 4). As in the previous study (18), in the present study, the orifices of the sinus were decongested. However, the opening of the sinus does not completely account for posterior overestimation (18).

In the original experiments, Jackson et al. (19) observed that the error of measurement in lung specimens increased with a decreasing diameter of an initial stenosis. In the lung, an underestimation of the true airway cross-sectional area was noted (19). An initial constriction may cause energy losses (17) and cause overestimation in the areas behind the narrowing (29). The initial stenosis affected the homogeneity of the
frequency spectrum because impedance is frequency dependent (29). An influence of the anterior stenosis could not be supported by the data of the present study, as others also found (17).

Energy losses due to nonideal gas composition seem to be low in the nose because helium breathing did not have a significant impact on AR in the nose (17) in contrast to the trachea (9). Energy losses due to nonrigid behavior of the walls (viscous losses) can be significant in the trachea (21). However, experimental studies in the nose revealed a minor importance of viscous losses in the nose (17).

All systematic sources of error are supposed to contribute to the observed inaccuracy in the posterior nose to a certain extent. Their influence cannot be excluded for physical and anatomical reasons. The point is that their impact is constant in the individual patient, allowing for intraindividual comparisons. Within certain limits, their impact is also constant interindividually, and the development of a compensation algorithm for AR based on further comparative measurements should be possible. However, Jackson and co-workers (19) have defined that a series of cross-sectional areas are recovered from the reflected wave, representing an acoustic system equivalent to the anatomic properties of a nose, not conclusively equivalent to the acoustic properties. Thus an absolute identity of the acoustic and the anatomical area-distance curve cannot be expected for physical reasons.

In conclusion, accepting the CT data and the definition of individual measuring planes in the present study as a gold standard, a high measuring accuracy was found for the anterior nose, the nasal valve, and the nasal isthmus. This suggests a diagnostic use of AR for intraindividual and interindividual comparison of the anterior parts of the nose.

The measuring planes follow the individual propagation of the sound waves on a curved line through the nasal cavity. Thus comparing the area-distance curve determined by AR with real distances in the nose on a straight line from the nosepiece to the pharynx is questionable. The same applies to assessment of the nasal volume by simple integration of the area-distance curve. In the posterior nose, the measuring accuracy was unacceptable. Because of good reproducibility, intraindividual comparisons are possible.

REFERENCES


