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# Accuracy of acoustic rhinometry*

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SUMMARY

Objectives: *The objective of this study was to evaluate the ability of acoustic rhinometry (AR) (Rhin2100, Rhinometrics, Lynge, Denmark) to accurately determine the dimensions (cross-sectional areas and volumes) of the curved and complex slit-like geometry of the nasal airway.*
Materials and methods: *A plastic model representing the replicate of a decongested nasal airway was produced by stereolithographic techniques from a 3-D MRI-scan. The exact dimensions of this model was determined from a high resolution CT-scan. Dimensions perpendicular to the curved course of the acoustic pathway were compared with dimensions inferred from parallel sections. The impact of sound loss to the paranasal sinuses and the ability to detect posterior volume changes was tested in the same model.*
Results: *The error in volume determination was <14% for the MCA and <8% for the volumes, whereas the error reached 52% for dimensions calculated from parallel sections in the coronal plane. The influence of the simulated maxillary sinuses depend primarily on the size of the ostia and may represent an important source of error for posterior measurements, in particular after decongestion.*
Conclusions: *The accuracy of acoustically derived dimensions of the 3-D model depend on the orientation of the planes used to calculate the dimensions of the model. Volume estimates based on the smallest cross-sectional areas in points along the acoustic pathway correlate well with acoustically derived volumes, whereas single cross-sectional areas are more susceptible to error. Sound leakage to patent sinus ostia reduce the accuracy of posterior measurements.*

*Key words: acoustic rhinometry, accuracy, model study, nasal airway, sinuses*

## INTRODUCTION

Acoustic rhinometry (AR) (Hilberg et al., 1989) has due to its simplicity and non-invasive nature gained increasing popularity as a method for objective assessment of nasal patency. Still many issues related to the accuracy of AR remain unresolved. Dimensions described by AR represent cross-sectional areas perpendicular to the curved pathway of incident and reflected acoustic wave-front, limiting the value of validations performed in symmetrical straight tubular models. In addition, the curved course of the nasal airway complicates both interpretation and validity of comparisons between dimensions obtained by AR and dimensions derived from parallel sections of cadaver heads (Mayhew and O'Flynn, 1993), CT- (Gilain et al., 1997; Min and Jang, 1995; Hilberg et al., 1989) and MRI-scans (Corey et al., 1997; Hilberg et al., 1993).

The objective of this study was to compare acoustic rhinometric measurements in the complex nasal model with calculated dimensions perpendicular to the presumed acoustic pathway and with parallel coronal sections.

## MATERIALS AND METHODS

### *Acoustic rhinometry*

Acoustic signals generated in a sound wave tube are conducted via a nasal adapter to the nasal cavity under examination (Rhin2100, Rhinometrics, Lynge, Denmark). Analysis of the incident signal and its reflections from the nasal cavity provide both a graphic display of cross-sectional area-distance (AD) relationships and a numeric description of minimum cross-sectional areas (MCA) and volumes between selected points along the acoustic pathway in the nasal cavity (Hilberg et al., 1989).

### *The stereolithographic (SLA) epoxy model*

A volunteer was examined by an MRI scanner (Signa SP, 0.5 Tesla, GEMS, Milwaukee, WI) with a 3-D T1-weighted gradient echo sequence (TR/TE34/15 ms, flip angle 60°, slice thickness 2 mm). The images were exported to a workstation (Indigo2, SiliconGraphics, Sunnyvale, CA) with software for image analysis developed at the Interventional Center, The National Hospital, Oslo, Norway. The field of view was 24 cm × 19 cm, and the

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images were presented as a 256 × 256 matrix reconstructed in coronal, sagittal and axial views. A digital model of the nasal cavities was obtained by utilising level and edge detection algorithms. In addition, manual correction was performed to avoid the appearance of complete occlusions in the most narrow segments of the model. The digital voxel model was converted to a vector based graphic platform for smoothing sharp edges and production of an epoxy SLA model (VINN, Narvik, Norway). These modelling procedures obviously increased the dimensions moderately compared to the true dimensions of the MRI-scan and the AR performed immediately prior to the scan. CT scans of the epoxy SLA model (High-speed CT, GEMS, Milwaukee, WI) were performed to generate a voxel-based digital model with high resolution. This CT generated digital model consisted of 256 × 256 × 93 voxels (12 cm × 12 cm × 9.3 cm) that included the right and left nasal cavities. The voxels at the border zone with partial volume effect were defined as plastic or air according to the most dominant signal contribution. The remainder of the model was automatically segmented by intensity levels from plastic or air.

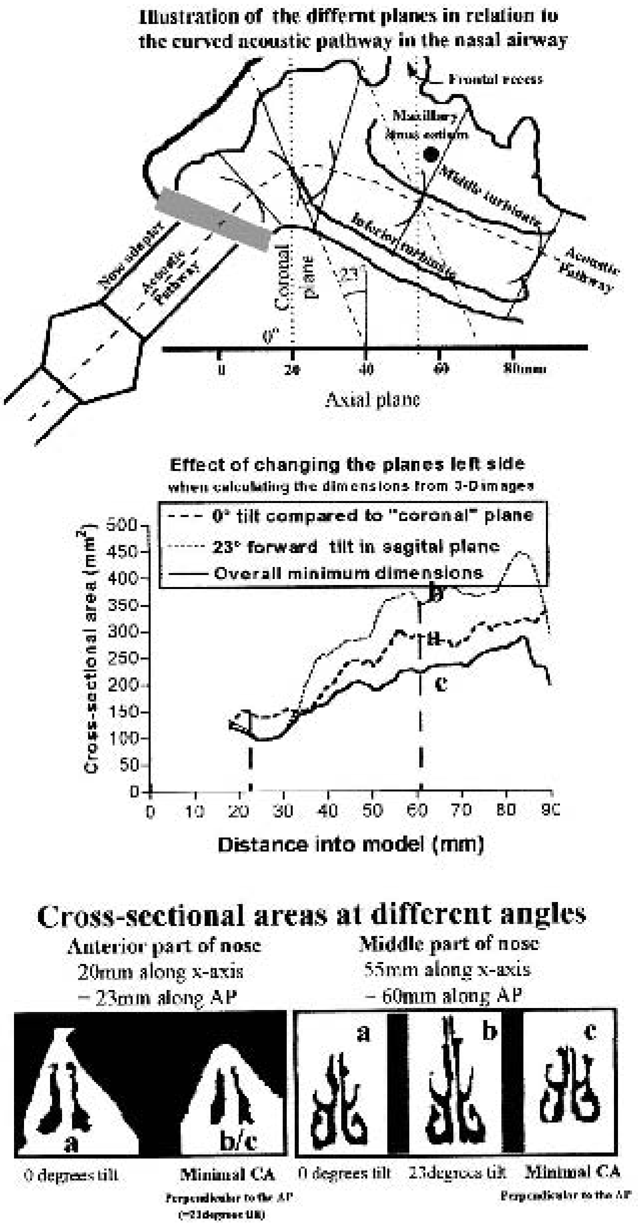


Figure 1. Upper panel: Relationship between anatomic structures in the nasal airway, the acoustic pathway (AP) and different angles of coronal planes. a) no sagital and axial rotation, b) 23° sagital rotation, forward tilted, c) overall minimum dimensions with varying sagital and axial rotations. Middle panel: The cross-sectional areas (CA) form parallel coronal CA's (0° and 23° tilt) compared to CA perpendicular to the presumed AP. Lower panel: Selected CA's in different coronal planes at the anterior and middle part.

A duct, 5 mm in length with an internal diameter of 3 mm was drilled at the location of the ostium to the maxillary sinus. A syringe with an internal tip diameter of 1mm was inserted into the artificial ostium and the volume of the simulated maxillary sinus varied by moving the piston.

A metal rod (diameter 4 mm, CA=0.13 $cm^2$) was introduced into the left nasal passage from posterior to determine the ability of AR to detect a reduction in CA corresponding to approximately 5% of the CA and volume.

The volume of the anterior 9 cm (along the acoustic pathway) of the two passages was determined by closing of the anterior opening of the model and installing water with a syringe into the model. The model was tilted so that the surface of the water corresponded to the plane perpendicular to the acoustic pathway at a depth of 9 cm (posterior septal edge).

*Calculations and Statistics*

The orientation of the parallel CT scan-planes, representing coronal planes of the model, was defined from a perpendicular axis to the planes directed 37° upward tilted from the posterior part of the acoustic pathway, in the turbinate region (Figure 1). Calculations of the cross-sectional areas were performed with different sagital and axial rotations around a perpendicular axis to the sagital and axial planes through the centre of gravity of the left and right nasal cavity section, respectively, in the coronal CT scans. A trajectory through all the centre of gravity points was presumed to estimate the acoustic pathway, left and right respectively. The smallest cross-sectional areas in locations along the acoustic pathway were calculated from the overall minimum area with varying sagital and axial rotations.

Calculations and presentation were performed using PRISM Graph Pad 2.01. Accuracy of the MCA and volumes were expressed as the difference (% error) between the mean rhinometric curve and the dimensions obtained from the different planes chosen. The optimal rhinometric curves obtained with patent and occluded orifices simulating the position and size of ostia communicating with maxillary and frontal sinuses of different volumes, were compared.

RESULTS

The smallest cross-sectional areas, both rotated in axial and sagital planes, along the nasal cavity were found to lie approximately perpendicular to the presumed acoustic pathway and correlated well with the estimated smallest CA's of the complex geometry in the 3-D model (Figure 1, 2). The error was low and always <14% (largest error for MCA right side: 0.77 vs. 0.89 $cm^2$)

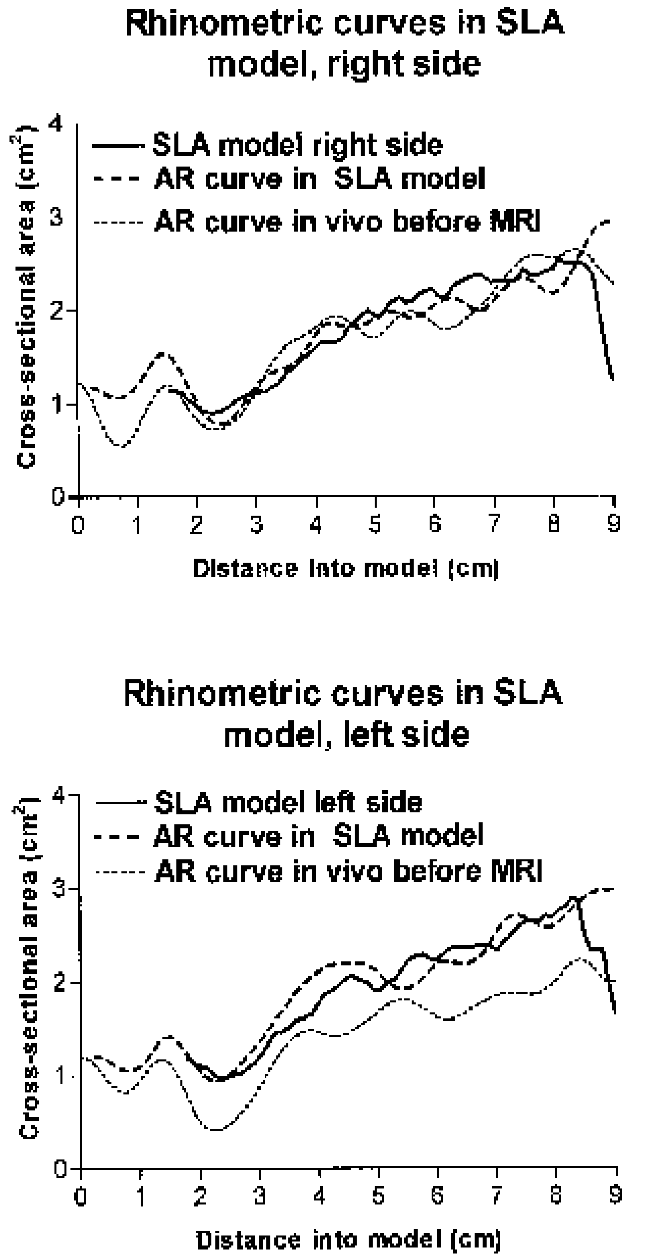


Figure 2. Comparison or AR curves in right and left nasal airway to the true dimensions of the SLA-model calculated perpendicular to the acoustic pathway (i.e. overall minimum dimensions with varying sagital and axial rotations).

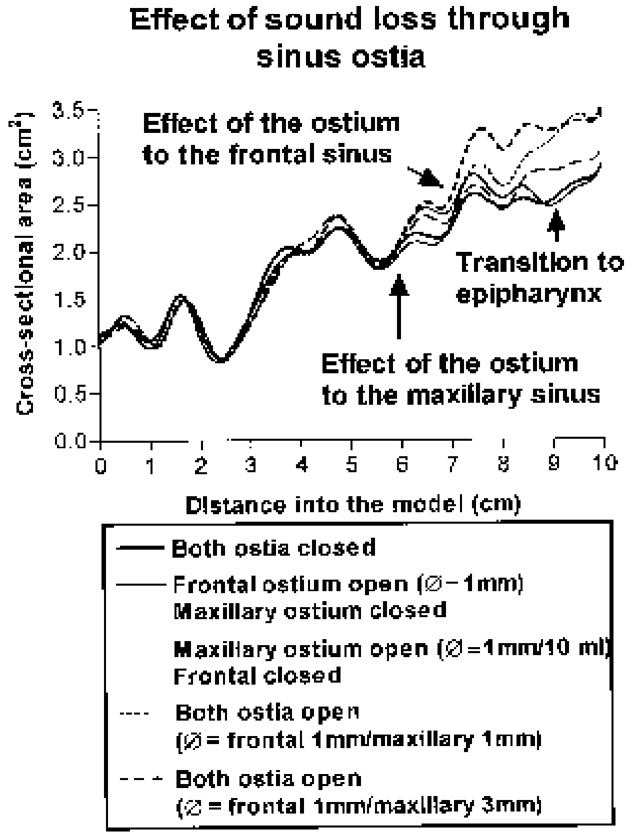


Figure 3. Illustration of the effects of sound loss through simulated ostia to the maxillary and frontal sinuses.

for the MCA and <8% (largest error for VOL 2-5 cm left side: 5.0 vs. 4.6 $cm^3$) for the volumes (Figure 1, 2). However, the error reached a maximum of +46% for MCA (largest error on left side: 1.38 vs. 0.96 $cm^2$) for dimensions calculated from parallel sections in the coronal plane and 52% (largest error on right side: 12.9 vs. 8.5 $cm^3$) for the volume from 2-7 cm (VOL 2-7) calculated from parallel planes tilted 23° (Figure 1, 2). The additional effect of rotation in the axial plane on the overall minimum CA's was negligible (not shown).

The smaller in-vivo AR dimensions on the left side (Figure 2) may be explained by a combination of incomplete decongestion at the time of the AR examination and the described manual adjustments of the MRI dimensions prior to the production of the SLA model, which increases relatively the dimensions primarily in the narrow parts of the passage.

| | MCA | %Diff. | Vol2-5 | %Diff. | VOL2-7 | %Diff. |
|---|---|---|---|---|---|---|
| Smallest dimensions (SLA model)-right side | 0.89 | | 4,3 | | 8,5 | |
| Smallest dimensions (SLA model)-left side | 0.96 | | 4.6 | | 9.0 | |
| Coronal plane - right side | 1,12 | 26 | 5,1 | 19 | 11,7 | 39 |
| Coronal plane - left side | 1,38 | 46 | 5,5 | 20 | 11,2 | 18 |
| Tilted 23° - right side | 0,91 | 2 | 6,0 | 39 | 12,9 | 52 |
| Tilted 23° - left side | 0,96 | 0 | 6,1 | 33 | 13,4 | 46 |
| AR curve - right side | 0,77 | -14 | 4,2 | -2 | 8,2 | -4 |
| AR curve - left side | 0,94 | -2 | 5,0 | 8 | 9,3 | 2 |

Table 1. Dimensions of the SLA model estimated form to different sets of parallel planes, the smallest cross-sectional area in each point along the presumed acoustic pathway. The difference compared to the smallest dimensions are given as percentages of the smallest dimension. The different curves are shown in Figures 2 and 3.

*Effect of sound leakage to the sinuses*

The effects of simulated changes in the dimensions of the sinus ostia and sinus volumes are shown in Figure 3. Measurements anterior to the sinus ostia were not affected by changes in the dimensions of the simulated sinuses (<2% change in VOL 0-6 cm). The narrow and relatively long frontal duct appears to have negligible effect on the acoustic measurements regardless of the volume of the frontal sinus (<3% change in VOL 6-9 cm with an open 1 mm frontal duct). Both the size of the ostium and the volume of the communicating sinus have some effect on the cross-sectional area and volumes posterior to the ostia. The larger the ostium and sinus volume the greater the effect. When both the frontal ostium (ø=1mm) and the largest maxillary ostium (ø=3 mm) were open, the overestimation of the total volume up to 9 cm reached 10%. The volume of the segment posterior to the location of the ostia (VOL 6-9 cm) was overestimated by as much as 23% compared to the curve obtained with both ostia closed (Figure 3).

*Detection of reduction in CA and volumes*

The 5% reduction in the volume induced by introducing the metal rod, was accurately detected (<10% error) (Figure 4).

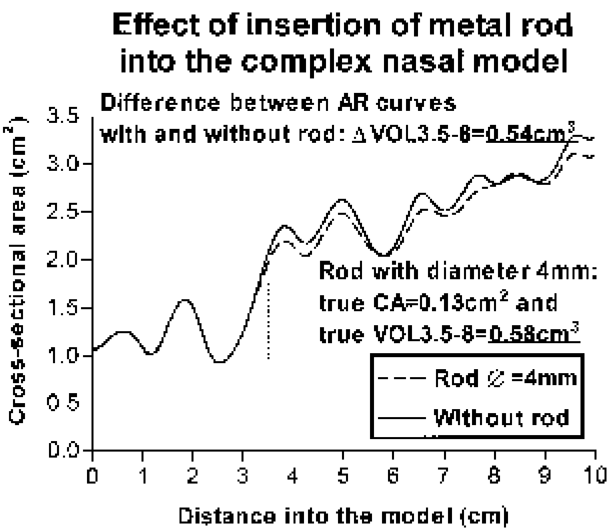


Figure 4. Illustration showing the effect of insertion of a metal rod into the complex nasal passage.

*Volume determined by instillation of water*

The volumes of the right and left passages from the nostril to the posterior margin of the septum were approximately 16 ml in both. The corresponding acoustically derived volumes (VOL 0-9) were similar; 17.3 ml and 16.5 ml of the right and left side, respectively.

DISCUSSION

The accuracy of acoustic rhinometry in the 3-D model is strongly influenced by the planes used to calculate the dimensions of the model. When the acoustically derived dimensions are compared with those calculated from the true minimum cross-sectional areas perpendicular to the presumed course of the acoustic pathway, the accuracy is excellent for volumes. The accuracy of single CA's is more variable.

Hilberg et al., (Hilberg et al., 1989) reported a fairly good, but variable correlation between CT-derived dimensions and acoustically derived dimensions. Buenting et al., (Buenting et al., 1994) found the acoustically derived volume to correlate well with the volume of a cast made from a cadaver of an infant and Mayhew & O'Flynn (Mayhew and O'Flynn, 1993) reported a high correlation with cross-sectional areas measured on sections from a cadaver head. Later studies comparing dimensions derived from parallel CT- and/or MRI scans and AR reported a fairly good correlation in the anterior part of the nasal airways, but much poorer further posterior (Gilain et al., 1997; Min and Jang, 1995; Corey et al., 1997; Hilberg et al., 1993). This can be explained by the parallel sections used in these studies, which are comparable to the parallel 'coronal sections' (0°tilt) applied to our model, also showing significant overestimation compared with AR (Figure 1).

The curved course of the sound path complicates and reduces the validity of simple integration of volumes which presume the pathway is straight. Since nasal volume determined by AR is derived from the products of CA and distance along the sound path, comparison is, thus, best performed by comparing AR derived dimensions to MRI/CT derived CA's along the same (or very similar pathway through the geometric means of the smallest CA's). The close agreement between the volumes determined by AR and instillation of water supports the validity of acoustically derived volumes in the complex nasal airway.

*Resolution of AR*

The ability to resolve abrupt changes in CA is related with the 'rise distance' and this ability depends primarily on the upper bandwidth frequency, on the algorithm used in the specific rhinometer software and the dynamic properties of the microphone (Djupesland et al., 1999). Constrictions and expansions

| | Vol0-6 | %Diff. | Vol0-7 | %Diff. | VOL0-9 | %Diff. | VOL6-9 | %Diff. |
|---|---|---|---|---|---|---|---|---|
| **Both ostia closed** | 9,4 | | 11,5 | | 16,5 | | 7,1 | |
| **Frontal 1mm-Maxill. closed** | 9,2 | -1,6 | 11,3 | -1,7 | 16,6 | 0,3 | 7,3 | 2,6 |
| **Frontal closed-Maxill. 1mm** | 9,3 | -0,6 | 11,6 | 1,0 | 17,0 | 2,7 | 7,6 | 6,9 |
| **Frontal 1mm-Maxill. 1mm/10ml** | 9,3 | -0,9 | 11,7 | 1,3 | 17,4 | 5,5 | 8,1 | 13,8 |
| **Frontal 1mm-Maxill. 3mm/10ml** | 9,4 | 0,0 | 11,8 | 2,6 | 18,2 | 10,0 | 8,8 | 23,1 |

Table 2. The influence of simulated open frontal and maxillary sinus osita sinuses on acoustic rhinograms in SLA model of complex nasal passage. The differences are expressed as the % difference from the rhinogram obtained with both osita closed. The corresponding rhinometric curves and location of the sinus are shown in Figure 4.

shorter than 3-4 mm may not be determined correctly due to technical limitations. It follows that single cross-sectional areas like the MCA becomes more sensitive to error than volume based on integrations of several CA's.

*Influence of sinuses*

In the nasal airway only a small part of the sound energy will reach the sinus ostia due to their remote and sheltered location behind the middle turbinate. This explains the much smaller influence of sound loss to the sinuses in vivo (Marais and Maran, 1994) than in the complex nasal models than in tubular models (Hilberg and Pedersen, 1996). Our results (Figure 3) confirm the potential influence of the sinuses on AR measurements and call for caution in interpretation of AR results posterior to 5 cm, particularly after decongestion.

Fortunately, the anterior 5 cm includes both the flow limiting valve area and a significant part of the erectile mucosa responding to physiological and pathological influences (Haight and Cole, 1983). Consequently, the volume of the anterior 5 cm (VOL 0-5) has been recommended as the volume of choice (Hilberg and Pedersen, 1996). The anterior 2 cm of the nasal passage is, however, lined mainly with squamous epithelium without erectile properties. Furthermore, the dimensions of the anterior 2 cm segment is more commonly affected by differences in positioning of the nose adapters (anatomical and conical). Consequently, we suggest reporting VOL 2-5 in addition to MCA and VOL 0-5 in AR studies of adults.

In infants, the small underdeveloped maxillary sinuses are not in continuity with the nasal passage, thus eliminating the potential influence by the sinuses (Wolf et al., 1993). A particular feature of AR is that the much smaller dimensions permit the use of a higher upper bandwidth frequency, which improves resolution (Djupesland and Lyholm, 1998). The sinuses may become a source of error beyond the age of 4 years when the middle meatus housing the sinus ostia become part of the functional respiratory tract.

*Detection of posterior volume changes*

The insertion of the rod indicate that AR designed for adults is sufficiently sensitive to detect volume changes of a magnitude of 5% in the posterior part of the nasal cavity (Figure 4). Fisher et al., found that spheres with a diameter of less than 7 mm inserted in a nasal cavity, could not be detected accurately by AR in vivo (Fisher et al., 1994). Detection of spheres is more demanding than of rods due to the described restrictions in spatial resolution and rise distance resolution. Furthermore, the characteristics relevant to AR designed for adults are not necessarily valid for infants and small children (Djupesland and Lyholm, 1998).

## CONCLUSIONS

Volume estimates based on the smallest cross-sectional areas in points along the acoustic pathway in the complex nasal model and water instillation, both correlate well with acoustically derived volumes. Single cross-sectional areas are more susceptible to error than volumes due to technical limitation of AR. Sound leakage via patent sinuses ostia reduces the accuracy of posterior measurements. The improved accuracy of AR when the curved course of the acoustic pathway is considered, further supports that AR is a reliable tool for rhinological research and clinical practice.

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