JURA NUMMINEN

Clinical Validation of Rhinometric Measurements

ACADEMIC DISSERTATION
To be presented, with the permission of the Faculty of Medicine of the University of Tampere, for public discussion in the main auditorium of Building K, Medical School of the University of Tampere, Teiskontie 35, Tampere, on April 11th, 2003, at 12 o’clock.
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To the noses I have met during this study!
MATERIALS AND METHODS 40

Patients 40
Methods 41
Statistics and software 45
Ethical consideration 45

RESULTS 46

Computer tomography volumetry in rhinometric measurements (I-II) 46
Accuracy of acoustic rhinometry evaluated with computer tomography volumetry (III) 48
Reference nose described with rhinometric methods (IV) 50
Comparison of rhinometric methods in healthy noses (IV) 52
Influence of upper respiratory tract infection and endoscopic sinus surgery in rhinometric measurements (V-VI) 54

DISCUSSION 57

Computer tomography volumetry in volumetric estimation of nasal airways 57
Accuracy of acoustic rhinometry 59
Reference ranges for rhinometric measurements 61
Rhinometric methods in clinics 64
The future of rhinometric methods 65

CONCLUSIONS 66

ACKNOWLEDGEMENTS 67
REFERENCES 69
ORIGINAL PUBLICATIONS 80
# ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ard1-2</td>
<td>Distance to the minimum cross-sectional areas from the nostril</td>
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<td>BMI</td>
<td>Body mass index</td>
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<td>CSA</td>
<td>Cross sectional area</td>
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<td>CT</td>
<td>Computer tomography</td>
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<td>CTV</td>
<td>Computed tomography volumetry</td>
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<td>HRCT</td>
<td>High resolution computer tomography</td>
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<tr>
<td>IARD</td>
<td>Image enhancement, amplitude segmentation, region growing and decision tree based segmentation algorithm</td>
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<td>ISCR</td>
<td>International Standardisation Committee for Rhinomanometry</td>
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<tr>
<td>MCA</td>
<td>Minimum cross-sectional area</td>
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<td>MRI</td>
<td>Magnetic resonance imaging</td>
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<td>NAR</td>
<td>Nasal airway resistance</td>
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<tr>
<td>NCV</td>
<td>Nasal cavity volume</td>
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<td>nPEF</td>
<td>Nasal peak expiratory flow</td>
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<td>nPIF</td>
<td>Nasal peak inspiratory flow</td>
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<tr>
<td>Pa</td>
<td>Pascal</td>
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<tr>
<td>PACS</td>
<td>Picture Archives Communication System</td>
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<tr>
<td>PEF</td>
<td>Peak expiratory flow</td>
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<td>PEFR</td>
<td>Peak expiratory flow rate</td>
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<tr>
<td>PIF</td>
<td>Peak inspiratory flow</td>
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<tr>
<td>SCAR</td>
<td>Standardisation Committee on Acoustic Rhinometry</td>
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<tr>
<td>VAS</td>
<td>Visual analogue scale</td>
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<tr>
<td>3-D</td>
<td>Three-dimensional</td>
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This thesis is based on the following publications, which are referred to in the text by their Roman numerals I - VI.


The publishers of the original articles have kindly granted permission to reprint the papers.
ABSTRACT

The purpose of this study was to evaluate: 1) computed tomography volumetry (CTV), a new semi-automatic segmentation method of computer tomography images based on image enhancement, amplitude segmentation, region growth, and decision trees, in the volumetric estimation of nasal airways, 2) the accuracy of acoustic rhinometry with the help of CTV, 3) the relationship between the different rhinometric methods; CTV, acoustic rhinometry, rhinomanometry, nasal peak expiratory flow (nPEF) meter and visual analogue scale (VAS) in healthy subjects as well as during mucosal pathology, and to create local reference ranges for minimum cross-sectional area (MCA), nasal cavity volume (NCV), nasal airway resistances (NAR) and nPEF rates. A total of 822 nasal cavities were studied in six different studies.

CTV proved to be well suited to the volumetric evaluation of the nasal cavity and paranasal sinus geometry and pathology with an average error less than 1.5 % in phantom test. However, CTV is still too expensive, slow and laborious for routine clinical work.

When the accuracy of acoustic rhinometry was evaluated using CTV as a reference method a strong statistically significant correlation were found up to 40 mm from the nostril \((r = 0.83, 0 – 10 \text{ mm} \text{ and } r = 0.77, 10 – 40 \text{ mm})\). Further posterior in the nasal cavity, the accuracy decreased, but remained moderate, \(r = 0.62\). The accuracy of single MCA values was much poorer without any statistical significance.

When the rhinometric methods were compared, the results were mutually consistent, but analysis of values did not confirm any statistically significant clinical agreement between the methods, \(r < 0.40\). A table of rhinometric reference ranges was produced for clinical use.

The methods improve diagnostics in rhinology, but none of the methods can replace any other, and different methods may be complementary. It is recommended to use at least acoustic rhinometry and rhinomanometry routinely in rhinological patients.
INTRODUCTION

The nasal cavities and paranasal sinuses are the first part of the airways, and normal nasal breathing requires a patent nasal airway. A patent nasal airway is one of the main factors, ensuring the function of the normal upper respiratory tract. In 1953 Proetz stated, “the functions of the nose are manifold as may well be expected of an organ which serves to prepare for use the breath of life” (Proetz 1953). In addition to air transport the nose and paranasal sinuses have functions such as olfaction, air purification, a physical filter, heat exchanger and humidifier for inhaled air. Nasal breathing is also a key factor in normal pulmonary physiology. A failure of any of these functions usually results in dysfunction of the upper or the lower respiratory airways. The latest view considers the airways as one unit from the tip of the nose to the alveoli, “The United Airways” (Passalacqua et al 2000).

Nasal disorders causing nasal obstruction are very common and nasal disorders such as allergies and infectious diseases of the upper respiratory tract seem to be increasing in incidence. It is, however very important that nasal disorders are thoroughly examined and the patient with rhinological problems is well cared for. In clinical rhinology, and in most scientifical studies, the congestion of the nose has been earlier evaluated by subjective assessment of obstruction or by using a single rhinometric method to evaluate the degree of obstruction. The intranasal geometry and function of the nose has been studied intensively with different objective methods in the last few decades.

Various objective methods have been applied to obtain intranasal cross-sectional areas, volumes and nasal airway resistance. The most common rhinometric measurement methods used in modern rhinology are acoustic rhinometry, rhinomanometry and nasal peak expiratory (nPEF) or inspiratory flow (nPIF) meters. Due to their simplicity and non-invasive nature these methods have gained increasing popularity among clinicians. Despite the widespread use of the methods, there are still many unanswered questions. Standardisation of these methods is a continuous process, and should be in accordance with the technical development and medical understanding of what we are measuring. Recently, the introduction of volumetric quantification of nasal cavities and paranasal sinuses such as
computed tomography and magnetic resonance imaging has provided some new opportunities in this area (Djupesland and Rotnes 2001).

The knowledge of the simultaneous use of different rhinometric methods in healthy and pathological noses has been relatively limited. Therefore it was decided to study the changes within one and the same method and correlations between different rhinometric methods. In addition, the reliability of acoustic rhinometry was evaluated with the help of high-resolution computed tomography (HRCT) volumetry. Finally the results were compared to subjective evaluation of nasal patency both in healthy and pathological noses.
REVIEW OF THE LITERATURE

History of rhinometry

Rhinometry is a general term for measurements of the various nasal parameters. One of the earliest articles on rhinometric measurements was published in 1894 in Archives of Laryngologica and Rhinologica (Zwaardemaker H. 1894). Zwaardemaker measured the nasal cavities by observing the humidity areas, forming on a mirror when a subject was breathing through the nose. The following year, Kayser studied one modification of passive rhinomanometry in which an artificial airflow was led through the nose and the differences in pressure were measured (Kayser R. 1895). Over fifty years later the modern rhinometric measurements saw the light of day, when Aschan, Drettner and Ronge described the principle of modern rhinomanometry in 1958. In this principle the patency of the nose is calculated by simultaneous measurement of nasal airflow and transnasal pressure difference (Aschan G. 1958). A decade later the theoretical basis for acoustic methods were discovered, when Ware and Aki described an algorithm which was the base for measuring cavity dimensions by use of sound (Ware 1969). Jackson and co-workers developed the idea further and provided the method including hardware and software for measurements in the airways (Jackson 1977).

At this point of trajectory, pulmonary medicine contributed the development of rhinometric methods. In 1973, Taylor and co-workers introduced recording of the nasal peak expiratory flow rate with a Wright peak flow meter (Taylor 1973). A few years later, Youlten presented a peak inspiratory flow meter, which was largely an inverted mini-Wright peak flow meter (Youlten 1980).

Since the 1980’s the rhinometric development has taken several big steps forward with the help of computer technology. The International Standardization Committee for Rhinomanometry (ISCR) published the committee report with recommendations on rhinomanometry in 1984 (Clement 1984) and the methodology of the rhinomanometry was re-
evaluated in healthy subjects and rhinosurgical patients in studies made by Sipilä with his associates (Sipilä 1991). In 1994 the Standardisation Committee on Objective Assessment of the Nasal Airway was founded with several subcommittees including also rhinomanometry and acoustic rhinometry.

Acoustic methods also advanced rapidly from the late eighties to the late nineties. At the end of the eighties, Jackson started a new age of rhinometric measurements. In 1987, Jackson et al. developed a new rhinometric method based on Ware and Aki’s theory of measuring cavities by acoustic impulses. They provided hardware and software for the initial measurements, and also suggested that the area distance curves were best portrayed with the logarithmic scales (Jackson and Lutchen 1987). Jackson and Hillberg and co-workers developed the method further, and the first commercial version of acoustic rhinometry as a rapid, non-invasive technique to study the intranasal geometry was presented in 1989 (Hilberg et al. 1989). Since then several commercial versions of acoustic rhinometry have been presented. At this point a triumphant procession of acoustic rhinometry began in rhinology. At least 300 studies have been reported since then, and the method has been evaluated in clinical practice for example in septal surgery and in nasal provocation tests (Hytonen and Sala 1996; Pirila and Tikanto 2001). The Standardisation Committee on Acoustic Rhinometry (SCAR) published the committee report with guidelines on the use of acoustic rhinometry in 2000 (Hilberg and Pedersen 2000), but the standardisation procedure is ongoing to this day.

The latest rhinometric methods are based on expanded use of digital imaging methods, such as computed tomography (CT) and magnetic resonance imaging (MRI). The principle is based on segmented images (Dastidar 1996), which are implemented using a combination of image processing tools, such as filtering, amplitude segmentation (Jain 1989), region growing (Glassner 1990; Pratt 1991) and image fusion. Segmented CT/MR images can be analysed and utilised in numerous applications, for example, volumetric analysis of different tissues. These methods have also been used in validation studies of other rhinometric methods.
Methods of rhinometry in rhinology

Acoustic Rhinometry

Acoustic rhinometry is an objective method enabling measurement of the relationship between the cross-sectional area of the nasal cavity and the distance into the nasal cavity. The method is based on the analysis of sound reflection from the nasal cavity taking into account the properties of incident sound submitted to the nasal cavity, along with associated reflected sound waves (Hilberg et al 1989).

The acoustic rhinometry measurement is done after a short period of acclimatization in a room with optimal environmental conditions. Subjects are in a sitting position and the measurement is done during the breathing pause. It is advantageous if it is possible to use a head stabilising apparatus during measurement. An airtight connection from the nosepiece of the apparatus to the nostril is accomplished with the help of gel. Another option is to use intranasal probes, which ensures airtight connections. These probes disturb the normal anatomy of vestibulum area, and can be used only in specific measurements of mucosal reasons such as during provocation tests (Pirila and Nuutinen 1998). The measurements are then performed, and the computer automatically calculates a volumetric analysis. Two different methods are available for the performance of acoustic rhinometry. The older one is based on the principle by which the examination is done using a sound pulse technique. In this method a sound pulse is generated by a spark, which propagates in a sound tube and enters the intranasal cavity through a nosepiece. In the nasal cavity it is reflected by local changes. A microphone in the sound tube then measures these incident and reflected signals from the nasal cavity. The newer technique is using a continuous sound signal, but otherwise it is identical to the older one (Djupesland et al 1999).

The SCAR guidelines have been given for measurement of nasal geometry with acoustic rhinometry (Table 1), but the standardisation of acoustic rhinometry is still ongoing and the report is merely a current consensus from the subcommittee.
Table 1. Summary guidelines for quality control and optimal application of acoustic rhinometry according to SCAR (Hilberg and Pedersen 2000)

1. A well-defined standard nose is used for testing and optimising the equipment.
2. Procedures for evaluation of accuracy and repeatability of measurements in the standard nose are presented, and error limits are defined for the area-distance curve as a whole, for the minimum cross-sectional area and for the volume 0-5 cm into the nose.
3. Publication of results should include the volume 0-5 cm into the nose (volume from 2-5 cm for mucosal changes), the minimum cross-sectional area or preferably the two first minima and the distances to those areas.
4. The operator should be trained, follow a standard operating procedure and the environmental conditions (temperature and noise) should be controlled.
5. Attention should be given to the nosepiece and the coupling between the equipment and the nose to obtain correct position and sufficient seal without disturbing the anatomy.
6. The manufacturer should provide information about the performance of the equipment, calibration procedures and maintenance, hygiene, environmental and safety standards.

The sources of technical errors and limitations in acoustic rhinometry measurements are well known. The most common source of error is air leakage from the nosepiece where it is fitted to the nose. Other errors are sound signal leakage to the opposite side of the nasal cavity in the posterior part of the nasal cavity, severe occlusions in intranasal anatomy, completely obstructed nasal cavity and environmental factors such as noise, temperature and also physical strain before the examination affects the results. It is also preferable to calibrate the instrumentation on a regular basis and sometimes it is useful to check the accuracy of the measurements using a so-called standard nose (Hilberg and Pedersen 2000).
Rhinomanometry

Rhinomanometry is an objective method for the examination of respiratory function. The method is based on the simultaneous registration of nasal airflow and the difference between the pressures in the nasopharynx and in the anterior part of the nose. Several different rhinomanometric methods have been developed during the last decades.

Passive rhinomanometry is a method where an artificial airflow is blown through the nose and the resulting pressure gradient is measured and defined as intranasal resistance. Passive rhinomanometry has been proved its availability for the evaluation of nasal reaction in intranasal provocation tests (Clement et al. 1978). More recently van Cauwenberge et al. and also Gleeson and co-workers confirmed the earlier findings but noted that the method was unphysiological, expensive and technically difficult (Gleeson et al. 1986; van Cauwenberge 1984).

Active rhinomanometry is a method in which the patient cooperates during the measurement by breathing spontaneously. Two different types of measurement can be taken; active posterior (Aschan G. 1958) or active anterior rhinomanometry (Masing and Frimberger 1974). In the posterior method the postnasal pressure is measured with a pressure catheter placed inside the oral cavity. The posterior method includes several disadvantages such as disconnection between the oral cavity and nasopharynx during measurement. The method is moreover highly sensitive to soft palate movements (Kortekangas 1972). The measurement may also be uncomfortable for the patient. Due to these problems the posterior method has not achieved the same popularity as the anterior method.

The most used technique in rhinomanometry is active anterior rhinomanometry. In 1974, Masing et al. introduced a variant of active anterior rhinomanometry using a whole-face mask with the pneumotachograph (Masing and Frimberger 1974). Later they developed the technique further by connecting the catheter to the nostril through an adhesive tape sealing the nostril (Masing 1979). In 1982, Broms et al. developed the method further by introducing a system for the numerical description of nasal airway resistance (Broms et al. 1979; Broms et al 1982). The ISCR has published a report on standardisation procedures for the use of active anterior rhinomanometry (Clement 1984).

The measurement of nasal airway resistance (NAR) by active anterior rhinomanometry should be based on ISCR guidelines (Table 2.).
Table 2. Summary guidelines for the measurement of nasal airway resistance according to ISCR (Clement 1984).

1. Active anterior rhinomanometry should be used in measurements.
2. Fixation of a pressure measuring tube is recommended to be done with the adhesive tape technique.
3. Any type of transparent and airtight mask that does not result in deformation of the nose is acceptable.
4. Two types of the pneumotachograph can be used: the lamellar and the diaphragmal pneumotachograph.
5. Performance of the calibration procedures and maintenance, hygiene, environmental and safety standards should be well fulfilled.
6. The patient should be in a sitting position and have a rest period of at least 30 minutes prior to measurement. The recording should be performed during quiet breathing.
7. Rhinomanometric results should be expressed in Pa/cm$^3$/s. The reference pressure was determined at 150 Pascal, and for those using the Broms mathematical model the expression of the resistance at radius 200 in a polar co-ordinate system is considered to be equally good.
8. A minimum of three to five breaths should be recorded.

In 2000, Carney et al. presented a modification of the ISCR report, which is a more time-consuming revised protocol involving multiple recordings and the identification and exclusion of erroneous data. Carney and his associates called it the “Nottingham Protocol” (Table 3.) and concluded that their results were more reliable and reproducible compared to measurements according to the ISCR guidelines (Carney et al 2000).
Table 3. The Nottingham Protocol for rhinomanometry (Carney et al. 2000)

1. Acclimatisation of the patient in a quiet room for 20 minutes
2. Rhinomanometry explained to a patient.
3. Adhesive tape technique is used.
4. Four nasal inspiratory-expiratory cycles (duration 6 s) are recorded at fixed pressure of 150 Pa.
5. Change of nostril is done and the opposite side is measured as above.
6. Two repeated recordings with a fresh tape each time on both sides are performed.
7. The mean of > 12 sets of data are calculated for inspiration in each nostril.
8. If any of the readings are outside 2 times standard error of the mean it should be excluded and a further set of four measurements performed.
9. Finally accept the mean inspiratory resistance for each nostril.

The sources of technical errors in rhinomanometric measurements are well known. In 1986, Pinkpank emphasized the correct fitting of the facemask, closure of the mouth during the measurement, the tight sealing and the avoidance of distortion of the nostril (Pinkpank 1986).

Nasal peak expiratory and inspiratory flow

Peak expiratory flow (PEF) meters were initially developed to diagnose and monitor the function of the lower airways in asthma patients. In 1959, Wright and McKerrow developed the method and equipment (Wright 1959) and in 1978 Wright developed the method further and presented a mini-Wright peak flow meter (Wright 1978). The mechanism of the mini-Wright peak flow meter is based on a piston, which is connected to a decelerating yew and movies by the force of expiratory or inspiratory blow through the airways. On breathing in through the PEF/PIF meters, a cursor moves along the scale to indicate the expiratory or inspiratory flow. PEF/PIF measures the maximum outflow or inflow of air with duration of at least 10 msec.
from the airways. The normal peak expiratory flow rates (PEFR) for the lower airways depend on the subject’s age, height and sex.

In 1973, Taylor and co-workers introduced recording of the nPEF rate with a Wright peak flow meter (Taylor 1973). Seven years later, Youlten introduced a PIF meter, which was in principle an inverted mini-Wright peak flow meter (Youlten 1980). For the measurement of nasal expiratory/inspiratory flows it is necessary to attach a facemask. The advantages of nPIF meter are that it measures better the function of nasal valve. However, the nasal valve can disturb the evaluation of erectile nasal mucosa.

The right technical performance of measurement is a crucial for reliable results. In a proper performance the subject should inhale/exhale fully, hold the PEF/PIF meter horizontally, and ensure that the facemask forms an airtight seal around the nose. After this, the subject should exhale/inhale forcibly through the nose. The manoeuvre should be a short and sharp action lasting about 1 to 2 seconds. The measurement should be repeated three times and the highest result used.

If the subject’s co-operation is lacking and the technical performance is not optimal the method entails several possibilities of error in measurements. Wrong blowing technique, weak or forceless blow, air leakage due to a leaking connection between the face and the apparatus and coughing, spitting or nasal secretions during measurement causes inaccurate rates (Connolly 1987).

**Radiological methods used as rhinometric measurement**

Various digital imaging methods, such as MRI and CT are widely used in clinical rhinology. During the last decade advances in new techniques have increased the indications of these radiological methods in rhinology. MRI and CT images have been used in several studies to produce rhinometric parameters. These parameters have often been compared to other rhinometric parameters such as cross-sectional areas and volumes obtained with acoustic rhinometry (Gilain et al 1997; Hilberg et al 1993). Radiological methods as the only rhinometric method in clinical or scientific studies are not a standard procedure.
The modern capabilities of image processing make radiological techniques a potential new method within rhinometric measurements. For example, digital images enable segmentation, where different tissues such as air and mucosa and different organs are recognised and classified using a computer. Several automatic and semi-automatic methods have been developed for segmenting particular structures (Dastidar 1996; Freeborough 1997; Hu 1990; Jack 1989; Saeed 1997; Seutens 1993; Wagner 1995). Segmentation procedures are implemented using different image processing tools such as amplitude segmentation (Jain 1989), filtering, region growing, image fusion etc. Segmented MR and CT images can be analysed and utilised in several applications. One of these possibilities is volumetric analysis of segmented images. Previously known dimensions including the thickness of the scans make this possible.

Sources of methodological errors in volumetric measurements with segmented digital CT or MRI images have been the subject of only a few studies. According to van Waesberghe different scanners, patient movement, patient repositioning, and large slice thickness may cause variations in volumetric studies (van Waesberghe 1996).

Other rhinometric methods

In addition to the previously named rhinometric methods some other methods have been proposed for rhinometric measurements. The use of these methods has still been quite limited and in the future, after further technical development, some of these methods may prove more interesting in clinical and scientific use. Some of these methods are rhinostereometry, forced oscillation technique, manometric rhinometry, and nasal spirometry.

Rhinostereometry is an optical method in which the nasal mucosal swelling is recorded by a microscope. In this method the nasal cavity is placed in the co-ordinate system and the nasal mucosa is examined through the eyepiece of the microscope. The eyepiece is equipped with a horizontal millimetre scale, which is used to measure changes in the congestion of the nasal mucosa (Hallen and Graf 1999; Juto and Lundberg 1982). The method is relatively complicated, and time consuming compared with other rhinometric methods. The future of rhinostereometry may be in
standardised provocation studies with histamine or allergens, and in other specialised applications such as laser Doppler (Ellegård 2002).

Forced oscillation is a technique where nasal airflow resistance is calculated as the difference between the total respiratory resistances measured at the nose and the mouth (Lorino et al 1998).

Manometric rhinometry is based on Boyle’s Law of Gases. In this method a known volume of gas is extracted from the nasal cavities and paranasal sinuses assuming that no change in temperature is occurring. The pressure change is measured and then the original volume can be calculated (Porter 1995).

Nasal spirometry is an ordinary spirometer attached to a facemask, which makes it possible to use a spirometer in nasal measurements. The spirometer produces flow-volume loops and calculates several parameters of airflow such as nPEF and nPIF values (Harar et al 2001).
Mathematical background of rhinometric data

Nasal airflow physics

Recently, in the literature the link between the upper and lower airways has been underlined by several epidemiological and clinical studies (Ciprandi et al 1996; Passalacqua et al 2000; Scadding 1994). Regarding the aerodynamic aspects of the functional unity of the upper and lower airways this link has been known for a longer time, but there are still questions which merit intensive discussion.

Infants are preferable nose breathers, and a preference for nasal breathing persists into adult life. About 85 % (Niinimaa 1980; Niinimaa 1981) of normal adults are nose breathers who resort to oral or oronasal breathing only under demanding conditions of exercise, voice use, and nasal obstruction (Swift 1977). Normal subjects begin to augment nasal with oral breathing at a ventilation of about 35 l/min and at this point 60 % of their respiratory air ventilation continues to pass through the nose. With a total ventilation of 90 l/min, 40 % of respiratory air continues to pass through the nose (Saibene 1978). Thus the normal nasal airflow function is essential for optimal respiratory function.

Nasal airflow patterns have been studied in cadavers and in models using smoke or water with dye or particles to visualise flow patterns (Fischer 1967; Mink 1920; Mlynski 2001; Proetz 1953; Swift 1977). In 1977, Swift and Proctor studied flow direction and velocity at different parts of the nasal cavity with the help of an anglemeter, which was passed through a transparent septum. They found that on inspiration at rest air passes first vertically upwards through the anterior naris at a velocity of 2-3 m/sec. After that, when the laminar flow is passing through the vestibulum area and nasal valve the flow changes from vertical to horizontal and the speed accelerates up to 12-18 m/sec. Behind the valve area the flow velocity decreases, turbulent flow persists, and most of the air flow continues horizontally along the middle meatus into the nasopharynx, as shown in Figure 1. (Swift 1977).
In a recent German study, Mlynski and co-workers evaluated detailed streamlines, flow distribution, and turbulence behavior (Mlynski 2001). They used modified “Mink’s boxes” (Mink 1920) and nasal models constructed from cadavers. Water with the help of traces of dye injected into the water was run through the models. The flow patterns were judged by the naked eye and recorded on video. It was found that in the vestibulum area, the airflow is redirected towards the area of the turbinates, and the laminar flow is stabilized. In the isthmus nasi, the airflow streamlines diverge, and when the airflow reaches the anterior cavum with increasing cross-sectional area turbulence increases and the velocity of airflow decreases. In the area of the turbinates, the streaming airflow particles come into contact with the nasal mucosa, and in the posterior part of the nose, which represents the outflow tract, direct investigation of airflow could not be performed. The authors speculated that in the posterior part of the nasal...
cavity the opposite effect happens compared to the anterior part of the nose (Mlynski 2001).

Nasal resistance

The nose acts as a variable resistor and accounts for as much as 40% of total airway resistance (Hilding 1976). 7 flow resistive segments can be pointed out in the respiratory airways. In the nasal cavities 2 segments are found. The first is the nasal valve region, which contributes to vestibular airflow resistance varying the shape and size of the vestibule and the valvular slit with the help of the alar muscles. The second is the nasal mucosa, which changes the cross-sectional areas (CSAs) altered by physiological mucosal activity and by pathological states. The other resistive segments in the airways are the soft palate, the mouth, pharynx, larynx, and trachea including the bronchial tree (Cole 1982).

Nasal airflow is a continuous and highly dynamic vital function, which is mainly dependent on the pressure difference between the nasopharynx and atmospheric air driven by intrathoracal respiratory mechanics (Lund 1989). Nasal airflow includes both laminar and turbulent airflow components, which vary during respiration. This leads to the fact that when the nasal airflow and pressure difference is observed, the relation between them is not linear, but rather sinusoidal. This has created a problem when resistance is defined mathematically. Several mathematical models to express nasal resistance have been proposed by many different authors during the last five decades. The basic ideas of these models has most often been to calculate resistance (R) at a certain pre-known pressure (P) gradient (R = P/V), V = nasal airflow. The most commonly used pressure gradients are 50, 75, 100 and 150 Pascal’s (Pa). Another mathematical model is based on the results presented by Broms in 1982, where the resistance is presented on a polar coordinate diagram with an x-y recording and the scale is produced so that pressure and airflow rates can be united. Three radii marked as 100, 200 and 300 are described, and the resistances are calculated in areas where the recorded pressure-flow curves intersects the arch of the chosen radius (Broms et al 1982). The ISCR recommends using resistances at 150 Pascal pressure or at radius 200 in Broms’ method in rhinomanometry measurements (Clement 1984).
Turbulence

Turbulent characteristics of airflow have been observed to have a physiological importance (Ingelstedt 1960). Fischer in his work studied turbulence and found that the nasal airflow is laminar at the lower flow velocity and turbulence increases at the higher flow velocities (Fischer 1967). Three years later, Clark with his associates observed that irregularities of the nasal cavity walls such as turbinates and surface fluid disrupt the laminar flow and increase the turbulence (Clark 1970). Mlynski et al. in Rhinology presented a similar kind of result. They found that at very low flow velocity up to 15 ml/s the airflow was laminar, and at a velocity of about 300 ml/s the airflow was completely turbulent. They also found, that the degree of turbulence and the amount of decrease in flow velocity seem to be regulated by congestion and decongestion of the erectile tissues of the head of the inferior turbinate and the nasal septum (Mlynski 2001). Turbulence creates a problem in the mathematical expression of nasal airflow, which leads to problems in the analysis of rhinometric data, especially concerning rhinomanometry results. In Röhrer’s equation both laminar and turbulent airflow are taken account (Röhrer 1915).

\[ P = k_1 V + k_2 V^2 \]

(P = pressure gradient, V = nasal airflow, k_1 = laminar flow and k_2 = turbulent flow). This equation has been criticized for being inexact for clinical use and instead of using Röhrer’s equation many authors are using the following formulas:

For laminar flow

\[ R = P/V \]

and for turbulent flow

\[ R = P/V^2 \]

(R = resistance, P = pressure gradient and V = nasal airflow)
Acoustic impulse in the upper airways

The theoretical background of the travelling acoustic sound pulse in the upper airways is quite simple, although in practice the technique, which uses acoustic waves (acoustic rhinometry), is based on strict assumptions and complex mathematical algorithms. The acoustic methods are based on the following principles.

The length of the measured tube is given by:

\[ d = ct \]

(\(d = \) tube length, \(c = \) wave speed and \(t = \) travel time)

The amplitude of the reflected pulse is given by:

\[ Pr = Po\left[\frac{(A_1 - A_2)}{(A_1 + A_2)}\right] \]

(\(Pr = \) amplitude of the reflected pulse, \(Po = \) amplitude of the incident pulse, \(A_1\) and \(A_2 = \) areas in two different points).

In a single straight tube the equation is valid, when constant and uniform gas composition is assumed. If instead of a single straight tube we have a cavity consisting of many segments, each having a different area, the pressure wave will be reflected in every part every time it encounters a new segment of the cavity. The measurement of the arrival times and amplitudes of the reflections permits the determination of the lengths and areas of the individual segments (Hoffstein and Fredberg 1991). Ware and Aki presented an analytic solution to the inverse-scattering problem for elastic wave propagation in stratified medium and practical computational procedures when the medium is probed with plane waves at normal incidence. The results they presented included about 100 different equations beginning with the transformation the equation of motion for wave propagation in a stratified elastic medium for plane waves at normal incidence into a one-dimensional Schrödinger equation (Ware 1969).

The interpretation of the acoustic data using the algorithm assumes that the pressure waves are a one-dimensional equation of motion, the gas
composition is uniform and if the airways are branching the algorithm does not recognize it as reliable.

These assumptions do not create practical problems when we use acoustic rhinometry. Most often the acoustic rhinometry we use produces and detects acoustic waves in the frequency range from 100 to 10 000 Hz. The speed of sound in air at 20°C and at atmospheric pressure is approximately 34 300 cm/s. Therefore, the shortest wavelength ($\lambda$) produced by an acoustic method (acoustic rhinometry) is 3.43 cm. The cross-sectional area of the nasal airway should be smaller than $\lambda^2$ (11.76 cm²). This means that when we analyse acoustic rhinometry measurements, there is no need to consider diffraction and interference effects (Cakmak et al 2001). During the acoustic rhinometry measurements gas composition may vary, but with CO₂ concentrations of about 5 %, the error introduced in the measurement of the area is negligible (D'Urzo 1986). In the case of branching the algorithm does not work. Fortunately, this situation is easily recognized in practice and does not disturb the measurements in the nasal cavities.
Validity of rhinometric data

Acoustic rhinometry

The validity of the acoustic rhinometry measurements has been an issue of great interest since the presentation of this method. Numerous research groups have validated acoustic rhinometry in plastic models of the nose, cadavers and living subjects. The volumetric results have been compared to different imaging modalities with encouraging results (Corey et al 1997; Gilain et al 1997; Hilberg et al 1993). The reliability, reproducibility and resolution have also been tested intensively.

The first observation described by the inventors of acoustic rhinometry was that the accuracy of acoustic rhinometry diminishes with distance from the nostril (Hilberg et al 1989). Hilberg and Pedersen subsequently reassessed the accuracy in more detail with the help of a standard nose. They defined accuracy as the difference between the model curve and the mean measured curve. They confirmed the earlier results, and reported the mean accuracy for acoustic rhinometry as 0.022 cm². They also measured deviation from the true values of the standard nose, which was less than 10 % (Hilberg and Pedersen 2000). Most recently, Cakmak et al. tried to identify factors that influence the accuracy of acoustic rhinometry using a simple model consisting of a metal pipe and cylindrical inserts. Different lengths and aperture dimensions of inserts were used and compared. They concluded that the cross-sectional area and passageway length of the narrow segment are the most significant factors affecting accuracy in measurements (Cakmak et al 2001).

Fischer et al. tested the resolution of the method in a study, where silicone spheres of 3.0, 5.0 and 7.0 mm diameter were placed at two sites in the nasal cavities of three subjects. The authors found that acoustic rhinometry detected 50 % of the 5.0 mm spheres and 100 % of the 7.0 mm spheres, and concluded that the resolution of the technique is close to 7.0 mm (Fischer 1994).

Hamilton et al. investigated the accuracy of acoustic rhinometry in acryl tubes with variable aperture areas, and found that the areas measured with acoustic rhinometry beyond narrow constrictions are particularly inaccurate. The authors noted that the true value of acoustic rhinometry lies in its
reproducibility, which was found to have a coefficient of variation of less than 5% in their study (Hamilton et al 1995). Tomkinson and co-workers confirmed these results by observing in turn that large changes in CSAs caused unreliable data beyond these changes (Tomkinson 1996c). Roithmann and co-workers investigated in more detail at the reproducibility of acoustic rhinometry. They measured 14 subjects over a period of five weeks in different study settings reaching recordings of over 3000 curves. The range for the coefficients of variation for minimum cross-sectional area (MCA) and nasal cavity volume (NCV) increased with the duration of the time interval between test-retest from 5% to 17% and from 4% to 9% respectively. The authors concluded that in non-decongested noses NCV values are more reproducible than MCA (Roithmann et al 1994). In 1999 a new reproducibility study from the same department in Toronto, Canada was published. This study concerned six subjects on six separate occasions within a 2-month period, and topical decongestants were applied. The mean coefficients of variation were 8.1±4.1% and 9.7±5.2% for MCA and 4.8±1.8% and 5.5±3.5% for NCV (0–50 mm) of the right and left sides (Silkoff et al 1999). In a Finnish study Nurminen et al. presented an application to calculate the reproducibility of acoustic rhinometry using a reproducibility correlation coefficient. They took 2400 measurements and calculated a reproducibility correlation coefficient (R = 0.65), and as an alternative measure they presented the mean coefficient of variation, 15% (Nurminen et al 2000).

The latest validation study was made with constant rate isotonic fluid infusion manometry, in which 10 healthy volunteers were measured before and after decongestion and the results were compared with acoustic rhinometry measurements. They concluded that volumetric changes in both methods are similar to anatomical changes in nasal vasculature, and acoustic rhinometry provides a sensitive, reliable and accurate assessment of vasoactive changes in the nasal cavity (Taverner 2002).

**Rhinomanometry**

The reproducibility and reliability of rhinomanometry measurements has been studied intensively in the last three decades. Some excellent results and also poor results have been reported in the literature. A study by
Kumlien and Schiratzki found a coefficient of variation as poor as 55% in baseline measurements and 27% in decongested nose (Kumlien 1979). Contrasting results are shown in a study in which Sandham measured 12 patients after decongestion with careful technical methodology and reported excellent results with a margin of error of the method from 1.4% to 5.2%. He also concluded that the variation between two repeated measurements is affected by recording procedure, air leakage, calibration of the instrumentation, and patient co-operation (Sandham 1988). In 1991, Sipilä in his doctoral thesis reported that there were no statistically significant differences between the two recordings, and neither the sex nor age of the patient had an effect on the reproducibility of the measurements. In his work he assumed that an acceptable intrasubjective variation in the same person between two measurements on two separate occasions was achieved if difference from their mean was less than 20%. In the power calculations he showed that both mathematical models, which are accepted by ISCR, showed this acceptable stability of recordings being under 20% (Sipilä 1991).

More precise measurements have been recommended by the Toronto Upper Airways Studies Group, which tested healthy subjects on six separate occasions within a 2-month period. For anterior rhinomanometry, they found the mean coefficients of variation to be 15.9 ± 7.3%, 12.9 ± 4.6% and 8.5 ± 2.8% for right, left and combined nasal airflow resistance respectively (Silkoff et al 1999). They concluded later that a mean coefficient of variation under 8% is adequate for clinical work (Cole 2000). This level of reproducibility can be achieved with modern equipment and careful methodology.

Nasal peak expiratory flow

The accuracy of PEF meters in pulmonary medicine is a well-studied field, because monitoring of peak expiratory flow is an essential part of the management of asthma. Several studies with a pneumotachograph or mechanical pumps have been done to verify the accuracy of this method (Folgering et al 1998; Miller 1992; Pistelli et al 1989). In 1989, Pistelli et al. noted that PEF results systematically overestimated PEF rate values when compared to pneumotachograph results (Pistelli et al
1989). Few years later, Miller et al. found that PEF meters were inaccurate and substantially overestimate flow in the range of 200 – 400 l/min (Miller 1992). Different types of peak flow meters were also evaluated with the help of a pneumotachograph in Nijmegen, Netherlands. Folgering et al. compared 11 different peak flow meters, for accuracy and linearity. The authors concluded that there were substantial differences between the meters (Folgering et al 1998). Observations of the effect of patient technique and training on accuracy were made in 1999, when Gannon et al. noted that under observation during clinical visits accuracy was significantly better than unobserved peak expiratory flow readings (Gannon et al 1999).

The accuracy of nasal peak flow rates has been studied less than pulmonary rates. Wihl and Malm investigated more detail seven peak expiratory flow meters and five peak inspiratory flow meters with an ejection and suction pump always giving the same flow of air. The meters were tested 20 times each. It was concluded that a patient ought to use the same flow meter each time throughout a study in order to reduce the dispersion of the values. Another observation made by Wihl and Malm was that with both peak flow methods the mean of three consecutive registrations gives a reliable measurement of nasal patency. In this way false maximal and false low values can be avoided. Finally they concluded that these factors emphasize the necessity for registration to be performed under supervision (Wihl and Malm 1988).

**Computed tomography volumetry**

Computer tomography volumetry results are based on image enhancement, amplitude segmentation, region growing and decision tree based segmentation algorithm (IARD) segmented data. In the literature there are only a few validation studies on methodology (Heinonen et al 1998a; van Waesberghe 1996). According to van Waesberghe some general factors may diminish reliability in the volumetric analysis of CT images. Different scanners may cause 1–2 % variability, patient movement and repositioning may cause 5–10 % variability, and large slice thickness may cause 0.1–7.5 % variability in volumetric studies (van Waesberghe 1996). One study with very good results is from 1998, when Heinonen and co-workers described
and presented new segmentation software for medical image processing. In this software the segmented data consist of classified voxels of known dimensions, and it was possible to compute the volume of a voxel. Therefore, the volume of a specific tissue can be easily computed as a product of the number of tissue voxels and the voxel volume. Hence, the accuracy of volumetric analysis depends on voxel size. To validate the volumetric accuracy of this software they segmented MR images of fluid filled syringes. Five syringes filled with fixed volumes of 1, 2, 5, 10 and 20 cm$^3$ of water respectively were imaged using T1- and T2-weighted MRI sequences. These syringes were fixed on the surface of a quality assurance filled with 2000 cm$^3$ of cupric sulphate solution. This simulated the head coil loading during a normal MRI scan of the head. All the MR images produced were segmented, and according to the measured volumes, the relative error of the total volume based on the syringe images was 1.5% (Heinonen et al 1998a).
Correlation between rhinometric measurement methods

Relationship between different volumetric methods

Comparisons of the intranasal cross-sectional areas and volumes obtained with acoustic rhinometry and different volumetric imaging modalities such as CT and MRI are not common. Some cadaver studies have been made with excellent results (Hilberg et al 1989; Mayhew and O'Flynn 1993). These studies revealed statistically significant correlations between MRI/CT and acoustic rhinometry with a correlation coefficient over 0.90. Hilberg et al. conducted one of the earliest studies with living subjects when they compared 10 healthy subjects with acoustic rhinometry and MRI scans with slice thickness of 3.5 mm in coronal plane. They found that generally the areas measured with acoustic rhinometry were about 15 % larger than the areas measured by MRI. The statistically significant correlation coefficient was 0.70 between the methods and they concluded that the sound axis roughly follows the geometrical axis (Hilberg et al 1993).

In a French study by Gilain et al. CT images of the nasal cavities were studied in 9 idiopathic rhinitis patients with inferior turbinate enlargement causing nasal obstruction. Scans in a coronal plane at 5.0 mm intervals were obtained, extending 8 cm into the nasal cavities. The intranasal geometry was calculated, and then compared to results obtained with AR. Statistically significant correlations were found between the methods in MCA1, MCA2 with $r = 0.73, 0.56$, and also in anterior, posterior and total volume with $r = 0.62, 0.27$ and 0.52. The authors claimed that CT could be used as a "gold standard" for validation studies of acoustic rhinometry (Gilain et al 1997). Similar results were reported from Chicago, Illinois, U.S.A. in the same year when Corey et al. evaluated five healthy subjects with acoustic rhinometry and the MRI images of 2.0 mm slices in coronal plane before and after the use of decongestant spray. Cross-sectional areas (CSA) did not correlate well in non-decongested noses ($r = 0.35$), but after decongestion a strong correlation ($r = 0.96$) was observed. I was also found that acoustic rhinometry measurements were higher than the MRI measurements, especially between 2 and 6 cm, and after the first 4 cm the correlation between the measurements was poor (Corey et al 1997).
Most recently Djupesland and Rotnes from Norway compared acoustic rhinometry and HRCT scans using a plastic model of intranasal airways produced by stereolithographic technique from a 3-D MRI scan. They found that error in volume determination was less than 14 % for the MCA and fewer than 8 % for the volumes. They concluded that volume estimations correlated well between the methods, but single cross-sectional areas were more susceptible to errors (Djupesland and Rotnes 2001).

Relationship between volumetric methods and functional methods

In 1994, Scadding et al. measured 10 patients with allergic rhinitis during nasal challenge with allergen using acoustic rhinometry and rhinomanometry. They compared MCA and total NAR results, and reported a significant negative linear correlation between the measurements with \( r = -0.6 \) (Scadding et al 1994). Tomkinson and Eccles who studied 51 healthy subjects with acoustic rhinometry, rhinomanometry, and visual analogue scale (VAS) obtained an opposite result compared to those of Scadding. They also investigated the relationship between MCA and NAR, and found a significant, but only a weak negative correlation between parameters with \( r = -0.27 \) (Tomkinson 1996a).

In Brussels, Belgium a clear relationship was founded in a study where 65 subjects including 50 patients with septal deviations and 15 healthy control subjects were measured with acoustic rhinometry, rhinomanometry and VAS. The main conclusion was that MCA correlated better with expiratory NAR than with inspiratory NAR (Szucs and Clement 1998). Silkoff and co-workers reported a completely inconsistent result in a study where six subjects were tested on six separate occasions with acoustic rhinometry and rhinomanometry. They found that mean CSA and NAR on the right side of the nasal cavities correlated well with \( r = -0.45 \), but on the left side of the nasal cavities and bilaterally mean CSA and NAR did not correlate at all with \( r = -0.33 \) and 0.24 (Silkoff et al 1999).
Relationship between different functional methods

Changes in nasal patency can be studied objectively with rhinomanometry as well as with nasal expiratory and inspiratory peak flow meters. As a subjective method, VAS is widely used to measure the degree of nasal obstruction. Comparisons between these methods have been made with contradictory results.

In a Swedish study made by Wihl and Malm 12 healthy adult subjects without actual nasal complaints were investigated with rhinomanometry, nasal expiratory and inspiratory peak flow meters. They recorded active anterior rhinomanometry, then five nPIF rate measurements, then repeated rhinomanometry followed by five nPEF rate measurements, and finally repeated rhinomanometry once again. The whole procedure was repeated after the use of nasal decongestants (Wihl and Malm 1988). They found significant correlations between NAR and nPEF rates ($r = -0.58$) and between NAR and nPIF rates ($r = -0.53$). A linear correlation between nPEF and nPIF values with correlation coefficients $r = 0.57$ before and $r = 0.77$ after decongestion was also seen in the results. Two years later, Holmström and co-workers confirmed the statistically significant negative linear correlation between NAR and nPIF values with $r = -0.35$ (Holmstrom et al 1990).

Relationship between objective and subjective methods

Objective methods have been compared to the subjective assessment of nasal obstruction with inconsistent results. It is not unusual that subjective perception of nasal obstruction conflicts with objective measurements: for example, Eccles and Jones studied nasal resistance and the sensation of nasal patency before and after 5 minute’s exposure to menthol vapour and found no consistent effect on nasal resistance to airflow, whereas the majority of subjects reported an increased sensation of nasal patency (Eccles and Jones 1983).

Fairley compared the relationship between VAS and nPIF values (Fairley et al 1993). Five subjects made a daily estimation of their subjective sensation of nasal patency following three measurements of nasal peak
inspiratory airflow rates. The measurements were repeated at least 25 times on different days. The authors concluded that the methods correlated strongly with each other, but this relationship varies between individuals (range for \( r = 0.37 – 0.87 \)).

Roithmann et al. compared VAS with acoustic rhinometry and rhinomanometry recordings in 78 randomly selected patients and found that VAS correlated well with unilateral MCA and NAR (\( r = -0.53 \) and 0.42 in non-decongested nose). In bilateral recordings no similar correlations were found (\( r = 0.11 \) and –0.07) (Roithmann et al 1994). Contrasting results were presented in the United Kingdom, where Tomkinson and Eccles studied 51 healthy subjects using VAS, acoustic rhinometry and rhinomanometry. They concluded that no correlation was seen between either acoustic rhinometry or rhinomanometry and subjective sensation (Tomkinson 1996a).

One year later, Simola and Malmberg from Finland published a study in which they compared VAS and rhinomanometry results from 102 patients during nasal histamine provocation. They concluded that a close relationship between the subjective assessment of nasal airway obstruction and NAR observed with VAS and rhinomanometry was found (Simola and Malmberg 1997). In Brussels, Belgium similar results were found in a study, where 65 subjects including 50 patients with septal deviations and 15 healthy control subjects were measured using acoustic rhinometry, rhinomanometry, and VAS. The authors concluded that VAS correlated better with NAR than with MCA (Szucs and Clement 1998). At the same time Hirschberg and Rezek reported supporting results from the study, where they measured VAS and rhinomanometry in 158 subjects. A statistically significant correlation was found between the subjective sensation of nasal obstruction and NAR bilaterally and unilaterally with \( r = -0.30 \) and –0.48 (Hirschberg and Rezek 1998).
Clinical applications of rhinometry

Studies in healthy noses

Rhinometric methods have been used for describing different aspects of nasal cavities in healthy subjects. Several hundred studies using rhinometric methods have been published during the last five decades. Some aspects emerge more frequently in these studies. Aspects like nasal airway physiology including nasal cycle, obstruction of the nose and effect of environmental factors on measurements have been studied. Reference values for healthy subjects have also been reported in many studies. For describing the normal intranasal geometry of healthy adult Caucasian subjects observed with acoustic rhinometry the following values have been presented in the literature. According to Marguez-Dorch et al. mean MCA was 0.68 cm$^2$, range 0.44-1.17 cm$^2$ in non-decongested noses and 0.78 cm$^2$, range 0.46-1.23 cm$^2$ in decongested noses. The NCV from 0-70 mm was 9.55 cm$^3$, range 5.61-15.93 cm$^3$, in non-decongested noses and 12.84 cm$^3$, range 6.53-19.67 cm$^3$, in decongested noses (Marquez-Dorsch 1996). Millqvist et al. found in turn that mean MCA was between 0.50 cm$^2$ and 0.69 cm$^2$ in healthy subjects in non-decongested noses (Millqvist and Bende 1998). Corey et al. presented similar results with mean MCA 0.52±0.12 cm$^2$ and NCV (0-80 mm) 8.25±5.23 cm$^3$ in non-decongested noses, and MCA 0.64±0.12 cm$^2$ and NCV 11.90±4.40 cm$^3$ in decongested noses (Corey et al 1998). For children of different ages similar reference values have also been found in some studies (Djupesland and Lyholm 1997; Pedersen et al 1994).

For the unobstructed nose NAR reference values have been described with the help of rhinomanometry. Sipilä and co-workers reported that the nose was unobstructed when unilateral NAR was under 200 Pa/l/s and total NAR was under 90 Pa/l/s at radius 200 in Broms’ method. Corresponding NAR values at 150 Pa were also calculated, unilateral NAR was under 300 Pa/l/s and total NAR under 150 Pa/l/s (Sipila et al 1994; Sipila et al 1992). Cole in turn defined unobstructed nose in adult subjects breathing quietly at rest when the total NAR was under 0.25 Pa/cm$^3$/s at 100 Pa (Cole 2000).
Nasal reference values for the PEFR are not defined in as much detail as for lower airways. In 1987, Goldman predicted nasal airflow values for nPEF calculating those from actual oral airflow values using the formula: 
\[ n\text{PEF} = 0.25 \times \text{PEF} \] (Goldman 1987). In 1986, Gleeson et al. reported normal values for nPIF and showed that nasal airway patency varies with time and nPIF rates may vary more than twofold in the course of a day. The normal rates for nPIF are assumed to be between 100 and 300 l/min (Gleeson et al 1986). Wihl and Malm described the normal rates for nPEF in non-decongested and decongested noses. The normal rates were from 325 to 379 l/min without decongestion and from 371 to 413 l/min in decongested nose (Wihl and Malm 1985).

**Studies in nasal pathology**

The clinical value of the rhinometric methods is the ability to measure the dimensions of the nasal cavity and describe the function of the nose. Acoustic rhinometry, rhinomanometry and nPEF describe nasal airway patency and give an impression of the degree of nasal obstruction. In addition, acoustic rhinometry and rhinomanometry provides parameters before and after decongestion, the cause of the nasal obstruction, mainly skeletal or mucosal to be evaluated.

Acoustic rhinometry and rhinomanometry are used as tools for diagnosis and follow-up of treatment in both rhinology and rhinosurgery. These have been used in septoplasty and turbinate surgery (Kemker et al 1999; Pirila and Tikanto 2001; Sipila et al 1994; Szucs and Clement 1998), in rhinoplasty (Constantian and Clardy 1996), in paranasal sinus problems (Lund and Scadding 1994; Sipila et al 1996a), and in sleep apnea patients (Antila et al 1997). Similarly, these methods are reliable methods to show changes in the nasal cavities before and after a given treatment, for example in allergic rhinitis patients (Clement 1997) or in the diagnosis of allergies in nasal provocation tests (Hytonen and Sala 1996; Pirila and Tikanto 2001).
AIMS OF THE STUDY

The purpose of the present study was to

1. Study the value of the semi-automatic segmentation of computer tomography images in the volumetric estimation of nasal cavities and paranasal sinuses.

2. Estimate the accuracy of acoustic rhinometry with the help of computer tomography volumetry.


4. Find out to what degree the acoustic rhinometry, rhinomanometry, nasal PEF and visual analogue scale recordings correlate with each other in healthy noses and during intranasal mucosal pathology.
MATERIALS AND METHODS

Patients

The clinical otorhinolaryngological examinations, rigid nasal endoscopies, rhinometric examinations and operative care and follow-up of the patients took place at the Department of Otorhinolaryngology, Head and Neck Surgery, Tampere University Hospital. The HRCT images were performed at the Department of Diagnostic Radiology, Tampere University Hospital and the segmentation of the images took place at the Ragnar Granit Institute, Tampere University of Technology. The material in Studies I - III and VI consisted of outclinic patients examined at the Department of Otorhinolaryngology. In Studies IV and V the subjects were selected on a voluntary basis from the Medical School and the College of Nursing in Tampere. In Study I 10 nasal cavities of 5 male patients aged 22 to 51 years suspected of having a chronic sinusitis were studied. Study II included 28 nasal cavities of 14 chronic rhinosinusitis patients (5 females and 9 males), who complained of nasal obstruction. Their average age was 39 years (range 19 - 69 years). Studies III and VI consisted partially of the same patients as Study II. 48 nasal cavities of 13 preoperative (5 female and 8 male patients) and 11 postoperative patients after endoscopic sinus surgery were investigated. Study IV included 249 healthy adult subjects (171 females and 78 males age range 19 - 40 years). 69 patients of these 249 previously healthy subjects, who were diagnosed as having acute viral rhinitis, were included in Study V. There were 47 females (average age = 23.7 years) and 22 males (average age = 23.3 years). Study I was a technical note.
Methods

Clinical examination including diagnostic nasal endoscopy

A medical history covering the exclusion criteria was taken. Patients with severe septal deviations, nasal polyposis or allergies were excluded from the study (Studies I-VI). A clinical otorhinolaryngological examination as well as a physical examination, was performed when needed (Studies I-VI) and included measuring of height and weight. The Body Mass Index (BMI) was calculated in Studies IV-V. The BMI is used to define nutritional status and is derived from the formula: weight in kilograms divided by the square of height in metres. A BMI of below 20 was considered to be underweight and a BMI of 20-25 to be normal. Subjects with BMIs of 25-30 were considered to be overweight and those with BMI over 30 as obese.

Nasal endoscopy was performed on patients in Studies I-III & VI. Topical anaesthesia combined with a vasoconstrictor was applied to the nasal cavities. The examination was then performed with 0° and/or 30° direction of view in endoscopes 4.0 mm or 2.7 mm in diameter. A general overview for orientation was done first, followed by an examination the passage along the floor of the nose up to the choana. Examination of the nasopharynx was performed. For the second step of the examination the endoscope was guided from the choana upward into the sphenoethmoidal recess and the posterior superior parts of the nasal cavities were examined. In the third step the endoscope was guided into the middle meatus, where the uncinate process, the hiatus semilunaris, and the ethmoidal bulla were examined. The endoscope was then guided in an antero-superior direction and finally the region of frontal recess was examined.

Acoustic rhinometry (I-VI)

An A1/2 acoustic rhinometry (G.M. Instr., Glasgow, UK) and programme version 3.02 were used for measurements. All measurements were performed after 15 minutes of acclimatisation and in a relatively quiet room.
at normal temperature (mean = 21.4°C) to minimize artefacts from physical stress, environmental noise and temperature changes (Corey 1996; Sipila et al 1996b; Tomkinson 1996b). The measurements were performed during a breathing pause while patients were in a sitting position. The nosepiece used in the measurements was 5 cm in length and was anatomically sculptured. To ensure a tight connection between the nosepiece and the tip of the nose, a small amount of ultrasound transmission gel was applied to the edge of the nosepiece. The angle of the incident acoustic impulse was about 45° with respect to a line running from the base of the piriform apertura of the nose to the tragus. MCAs and NCVs comprised a mean of 4 repetitive measurements. The technique we used allowed us to analyse 2 local minimum points giving us minimum cross-sectional areas (MCA₁ & MCA₂) and distance (ARd₁ & ARd₂) to the MCA points from the nostril. The software we used also produced 3 volume regions: anterior, defined as a region from nostril to 10 mm posterior, middle, from 10 mm to 40 mm and posterior, from 40 mm to 70 mm. In Studies I-III & VI all the volume regions were observed, but in the Studies IV-V only the middle volume region was measured.

Rhinomanometry (IV-VI)

A Rhinomanometry NR6 (G.M. Instr., Kilwinning, UK) version 1.1 was used for the measurements. The method consisted of using a compact computer unit, facemask and connecting tubes for the recording of both pressure and flow. All measurements were performed after 15 minutes of acclimatisation. The measurements were performed during normal breathing in a sitting position. The anterior active method was used and resistances at a radius of 200 according to Broms in a polar coordinate system were analysed (Broms et al 1979; Broms et al 1982). The technical arrangements and data calculations were made according to the recommendations of the ISCR (Clement 1984). Unilateral and total NAR values (Pa/l/s) in inspiratory and expiratory breathing cycles were measured.
Nasal peak expiratory flow meter (IV-V)

A Mini-Wright peak flow meter (Airmed, Clement Clarke International Ltd, London, UK) connected to an anaesthetic facemask (Flexomask, UK) covering the nose and mouth were used for nPEF measurements. Nasal PEF measures the maximum outflow of air (l/min) from the nasal cavities. The best of three attempts at blowing through the nose with the mouth closed was recorded and used for the calculations. Measurements were performed in a sitting position after a short period of acclimatisation.

Visual analogue scale (IV-VI)

The Visual Analogue Scale was used to measure the patient’s subjective degree of nasal obstruction (Studies IV-VI), postnasal drip and facial pain (Study VI); each side was measured separately. The nasal complaints were self-assessed by the patient using a 100 mm visual analogue scale. The ends of the scales were marked as complete absence of symptoms (0 mm) and completely affected by symptom (100 mm).

Computer tomography volumetry (I-III & VI)

Coronal HRCT images were performed on a Pro Speed PLUS scanner (General Electric, Milwaukee, Wisconsin, USA) with a tube voltage of 120 kV and tube current of 200 mA. The thickness of the processed coronal slices was 1 mm without intervening gap, field of view was 25 cm and matrix size was 512. Images were then processed with a semi-automatic segmentation programme called Anatomic. It utilizes the IARD method including several image-processing techniques, such as image filtering, amplitude segmentation, region growing, manual editing and image fusion. The segmented HRCT images were then also converted into cross-sectional areas and volumes as a function of the distance by algorithms, Figure 2.
Figure 2. Overview of the methodology for CT volumetric determination of nasal airways. Source images are obtained from CT scanner and stored to PACS archive. Anatomic software was applied in opening the images for volumetry. Using Anatomatic, original coronal CT image (A) was threshold in order to emphasize paranasal sinuses and classified using region growing technique (B). Thereafter this same procedure was carried out for nasal cavities (C). The segmented images (B+C) were combined (D) and according to voxel dimensions, the volumes and cross sectional areas were obtained automatically.
Consequently, 2 regions were defined by CTV to be representative of 2 local minimum cross-sectional areas. The CSAs and the distance from the nostril to these regions were calculated from the segmented HRCT images. The equivalent areas and volumes with acoustic rhinometry were also measured.

Statistics and software

The descriptive statistics were calculated in all studies and expressed as mean or median values with standard deviations or range values. The strength and direction of a linear relationship between the different methods was tested by the Pearson correlation coefficient test in Studies II-VI, and in addition with the Bland-Altman plots in Study III to observe the agreement between the acoustic rhinometry and CTV. Friedman's non-parametric test was used in Study V to evaluate the rhinometric changes during the infection. Analysis of variance for repeated measurements was used in Studies III and VI to examine the differences in pre- and postoperative nasal cavities. Determination of the power was calculated by T-test using PS Power and Sample Size Calculation software in Study VI. p values < 0.05 were considered significant. The correlation coefficient r > 0.40 was considered clinically significant (Dunn 1995).

SPSS for Windows releases 10.0 and 10.1 were used for the data analysis with five studies (II-VI).

Ethical consideration

The Tampere University Hospital Research Ethics Committee approved all the study protocols, and all subjects gave informed written consent. The principles of good clinical practice were followed in the trials.
RESULTS

Computer tomography volumetry in rhinometric measurements (I-II)

Semi-automatic segmentation of computer tomography images was tested in volumetric estimation of intranasal geometry and paranasal sinuses in 5 (Study I), and in 14 (Study II) chronic sinusitis patients with nasal obstruction. Volumes and cross-sectional profiles of the nasal cavities, paranasal sinuses, and some specific intranasal structures, such as chonca bullosa and Haller's air cells were automatically generated with CTV, Figure 3. In Study I, the accuracy of CTV was tested by segmenting HRCT images of fluid filled syringes with known volumes of water. In these phantom tests the relative error of the total volume was less than 1.5 %. The results showed that CTV was suitable and accurate method for geometrical measurements in the nasal airways. CTV results were then compared with acoustic rhinometry measurements as shown in Figure 4. The volumetric results seemed to correlate well in the comparison. Volumes and areas obtained with CTV were constantly larger than those measured using acoustic rhinometry. The relationship between the NCV and the degree of pneumatization in the paranasal sinuses measured with CTV was not seen. Accurate 3-D reformations of the segmented images were also obtained with CTV as shown in Figure 5.
Figure 3. Original and segmented CT images of 2 patients. The segmented profiles of the nasal cavities and paranasal sinuses are presented on the right side. In the lower patient, the segmented profile of the choncha bullosa is also presented.

Figure 4. One example of a segmented nasal cavity profile of one patient (A). The profile of the same patient obtained with acoustic rhinometry (C).
Figure 5. Three-dimensional presentation of nasal cavities and paranasal sinuses of one patient.

Accuracy of acoustic rhinometry evaluated with computer tomography volumetry (III)

A total of 48 nasal cavities with nasal obstruction associated with chronic sinusitis were measured using acoustic rhinometry and CTV. A comparison of nasal cavity volumes and minimum cross-sectional areas measured with these methods was made. The volumes measured from the nostril with both methods were the anterior (0-10 mm), middle (11-40 mm) and posterior (41-70 mm) parts of the nasal cavities. The distances of these 2 MCAs from the nostril were also measured and compared between the methods as shown in Table 5. The strength and direction of a linear relationship between the acoustic rhinometry and CTV data was tested by the Pearson correlation coefficient test. Agreement between NCVs obtained with these methods was also tested by Bland-Altman plots using 95 % confidence intervals.

Strong statistically significant ($p < 0.05$) correlations were found between acoustic rhinometry and CTV volumes in the anterior and middle parts of the nasal cavity. In the posterior part of the nasal cavity the correlation was
only moderate. Good agreements between the acoustic rhinometry and CTV volumes in the anterior and middle parts of the nasal cavities were confirmed with the Bland-Altman plots. Correlations among the MCAs were weaker and not statistically significant. The correlation coefficients are shown in Table 6.

**Table 5.** Distances from nostril to 2 minimal cross-sectional areas obtained with acoustic rhinometry and CTV.

<table>
<thead>
<tr>
<th>Acoustic rhinometry (cm) ± SD</th>
<th>CTV (cm) ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCA1</td>
<td>2.27 ± 0.44</td>
</tr>
<tr>
<td>MCA2</td>
<td>4.77 ± 0.62</td>
</tr>
</tbody>
</table>

**Table 6.** Correlation coefficients between acoustic rhinometry and CTV achieved with Pearson’s correlation coefficient test of 48 nasal cavities. NS = not statistically significance.

<table>
<thead>
<tr>
<th>Correlation coefficient</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior NCV</td>
<td>r = 0.83</td>
</tr>
<tr>
<td>Middle NCV</td>
<td>r = 0.77</td>
</tr>
<tr>
<td>Posterior NCV</td>
<td>r = 0.62</td>
</tr>
<tr>
<td>MCA1</td>
<td>r = 0.59</td>
</tr>
<tr>
<td>MCA2</td>
<td>r = 0.55</td>
</tr>
</tbody>
</table>
Reference nose described with rhinometric methods (IV)

Acoustic rhinometry, rhinomanometry and nPEF were carried out in 249 healthy adult Caucasian subjects (171 females and 78 males) without any severe rhinological pathology. Among females the mean BMI was 21.7 and among males the mean BMI was 23.8. Of the females 9 (5.3 %) were smokers and of the males 7 (9.0 %) were smokers. The reference nose based on this material is given in Table 7. The median values with ranges in MCA, NCV, NAR and nPEF are shown.

**Table 7. Results in the normal material (n = 498 in NCV, MCA and unilateral NAR recordings, and n = 249 in total NAR and nPEF recordings). Median values with ranges in MCA, NCV, NAR and nPEF.**

<table>
<thead>
<tr>
<th></th>
<th>Female</th>
<th>Male</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCA (cm²)</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>0.17-4.87</td>
<td>0.21-4.20</td>
<td>0.17-4.87</td>
</tr>
<tr>
<td>NCV (cm³)</td>
<td>3.11</td>
<td>3.14</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>1.25-15.1</td>
<td>1.25-18.39</td>
<td>1.25-18.39</td>
</tr>
<tr>
<td>Total inspiratory</td>
<td>28.8</td>
<td>29.1</td>
<td>28.8</td>
</tr>
<tr>
<td>NAR (Pa/l/s)</td>
<td>3.4-182.1</td>
<td>5.0-379.1</td>
<td>3.4-379.1</td>
</tr>
<tr>
<td>Total expiratory</td>
<td>29.2</td>
<td>30.1</td>
<td>29.7</td>
</tr>
<tr>
<td>NAR (Pa/l/s)</td>
<td>3.2-252.2</td>
<td>5.0-453.6</td>
<td>3.2-453.6</td>
</tr>
<tr>
<td>Unilateral inspiratory</td>
<td>60.5</td>
<td>61.9</td>
<td>60.7</td>
</tr>
<tr>
<td>NAR (Pa/l/s)</td>
<td>6.1-961.3</td>
<td>5.6-887.4</td>
<td>5.6-961.3</td>
</tr>
<tr>
<td>Unilateral expiratory</td>
<td>66.3</td>
<td>64.2</td>
<td>65.7</td>
</tr>
<tr>
<td>NAR (Pa/l/s)</td>
<td>5.7-1484.1</td>
<td>5.5-979.0</td>
<td>5.5-1484.1</td>
</tr>
<tr>
<td>nPEF (l/min)</td>
<td>295</td>
<td>395</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>140-460</td>
<td>200-620</td>
<td>140-620</td>
</tr>
</tbody>
</table>
The effects of gender, BMI and smoking habits were further analysed. Further consideration by subject gender did not significantly change the results. BMI did not have any effect on the rhinometric measurements. Smoking habits, however, clearly showed signs of having an effect on the results. In acoustic rhinometry the NCV and MCA were clearly smaller in smoking subjects than in non-smoking subjects. The difference was 10.56% in NCV and 9.12% in MCA. In rhinomanometry the NAR values in inspiration (8.75%) and expiration (11.0%) were larger in smokers. In nasal peak expiratory flow measurements the analogous decrease in values was 2.78%.

The reference ranges for rhinometric measurements were further calculated including 95 % of the values in this cohort, Table 8.

**Table 8.** Reference ranges in healthy young adults without any nasal complaints.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCA</td>
<td>0.26 – 2.39 cm²</td>
</tr>
<tr>
<td>NCV</td>
<td>1.53 – 9.32 cm³</td>
</tr>
<tr>
<td>Total inspiratory NAR</td>
<td>7.0 – 107.5 Pa/l/s</td>
</tr>
<tr>
<td>Total expiratory NAR</td>
<td>6.2 – 114.9 Pa/l/s</td>
</tr>
<tr>
<td>Unilateral inspiratory NAR</td>
<td>10.3 – 382.1 Pa/l/s</td>
</tr>
<tr>
<td>Unilateral expiratory NAR</td>
<td>10.2 – 448.1 Pa/l/s</td>
</tr>
<tr>
<td>Nasal PEF</td>
<td>175 – 520 l/min</td>
</tr>
</tbody>
</table>
Comparison of rhinometric methods in healthy noses (IV)

Acoustic rhinometry, rhinomanometry and nPEF recordings were compared in 249 healthy subjects. MCA, NCV, Ard, unilateral and total NAR in expirium and inspirium, and nPEF parameters were compared crisscross in all possible directions. The strength and direction of a linear relationship between the different methods were tested with Pearson’s correlation coefficient tests. Two pairs of the measured parameters correlated statistically strongly. A strong correlation between MCA and NCV was measured with acoustic rhinometry \((r = 0.959)\). The correlation between the NAR in inspiration and NAR in expiration measured with active anterior rhinomanometry was also very strong \((r = 0.977)\). The absence of any correlation between the other measured rhinometric parameters were noted \((r < 0.40)\), Figure 6.
Figure 6. Two examples of scatter plots, (A) correlation between MCA and NCV, and (B) correlation between nPEF and expiratory total NAR.
Influence of upper respiratory tract infection and endoscopic sinus surgery in rhinometric measurements (V-VI)

In Study V acoustic rhinometry, rhinomanometry, nPEF and VAS were performed on 69 patients with acute viral-induced rhinitis. The patients were selected from a pool of 249 previously healthy subjects (Study IV). Before the onset of an acute viral infection all subjects in the study underwent rhinometric measurements and these values was used as baseline values (day 0). Two to three days after onset of the viral infection the patients began the seven-day study. Rhinometric measurements including VAS were then performed on days 3 and 10 during the infection.

Statistically significant changes in intranasal dimensions and functional parameters were measured with all the rhinometric methods used in the present study ($p < 0.05$), Figure 7. Statistically significant volumetric changes were measured with acoustic rhinometry, MCA 20.0 % and NCV 20.4 % smaller than baselines during the early stages of the infection, and the partial recovery of nasal geometry was measured at the end of the infection, showing MCA 7.2 % and NCV 10.4 % smaller than baselines on day 10 ($p < 0.05$). In rhinomanometry the total NAR increased markedly during expiration and inspiration in the infection. On day 3 the values were 39.8 % vs. 41.6 % and on day 10 they were 34.1 % vs. 41.5 % higher than baseline recordings ($p < 0.05$). The nPEF rates reacted simultaneously with 25.0 % lower rates on day 3 and only 3.1 % lower rates on day 10 of the infection compared with baseline recordings ($p < 0.05$). The VAS measurements on day 3 and day 10 also yielded simultaneous results. The measurements obtained using acoustic rhinometry showed statistically and clinically significant correlation between MCA and NCV ($r = 0.96$). MCA and NCV comparison with the parameters of other methods such as NAR, VAS, and nPEF showed statistical significance but not clinical significance, $r < 0.40$, $p < 0.05$. Rhinomanometry also showed a statistically and clinically significant correlation between expiratory and inspiratory NAR ($r = 0.98$). NAR values compared to VAS and nPEF also correlated in a statistically but not clinically significant manner, $r < 0.40$, $p < 0.05$. 
Figure 7. Percentage (%) changes in acoustic rhinometry, rhinomanometry, nasal PEF and VAS during an infection of the upper respiratory tract.

The positive and statistically significant effect of endoscopic sinus surgery on nasal cavity volume and nasal function was clearly demonstrated with acoustic rhinometry, CTV, rhinomanometry and VAS in Study VI, Figure 8. In the middle meatal antrostomy group, the average postoperative volume measured with acoustic rhinometry was 0.90 cm$^3$ larger. In the ethmoidectomy group the average postoperative volume measured with acoustic rhinometry was 3.39 cm$^3$ larger. The results measured with acoustic rhinometry and CTV correlated well ($r = 0.72$) when the entire cohort was analysed together. When the middle meatal antrostomy and ethmoidectomy groups were analysed separately, the correlation between the methods was very strong ($r = 0.93$) in the ethmoidectomy group but poor ($r < 0.40$) in the middle meatal antrostomy group.

In rhinomanometry recordings the postoperative NAR values were significantly lower compared to preoperative recordings in both operative groups. However, the mean inspiratory NAR (188.7 Pa/l/s in the middle meatal antrostomy group vs. 202.3 Pa/l/s in the ethmoidectomy group) were still higher than the reference ranges defined in Study IV, Table 8. Agreement between the inspiratory NAR and nasal obstruction measured
with VAS was tested and resulted in a poor correlation ($r < 0.40$) when the entire cohort was analysed. However, the correlation between the methods was moderately strong ($r = 0.57$) in the ethmoidectomy group but again poor ($r < 0.30$) in the middle meatal antrostomy group.

![Graph A](image)

![Graph B](image)

**Figure 8.** Mean change in NCV (cm$^3$) measured using (A) acoustic rhinometry and (B) CTV between the pre- and postoperative visits. The broken line represents the ethmoidectomy group and solid line represents the middle meatal group.
DISCUSSION

Computer tomography volumetry in the volumetric estimation of nasal airways

Different imaging modalities such as CT and MRI have not been much used in the volumetric analysis of nasal airways. Some cadaver, plastic model and living patient studies have been done during the last decade (Corey et al 1997; Djupesland and Rotnes 2001; Gilain et al 1997; Hilberg et al 1993). The volumetric analysis in these earlier studies has usually been based on manual delineations of images and different kinds of algorithms, calculated by computers, and therefore direct comparison of the results obtained with CTV based on the IARD segmentation algorithm and other techniques is not possible.

According to the literature, the skull and head region have, however, been segmented from MRI with the IARD algorithm. Multiple sclerosis plaques and infarcts have successfully been segmented from conventional MRI images (Heinonen et al 1998b). Promising results from these MRI studies were one of the reasons why in Studies I-II the nasal airways were segmented with the IARD algorithm for the very first time in the literature. The semi-automatic segmentation of computed tomography images was tested in the volumetric estimation of nasal airways, and it was clearly demonstrated that accurate volumes of the nasal airways and also pathological changes such as chonca bullosa and mucosal thickenings in the nasal cavities and paranasal sinuses could be revealed with CTV. An average error less than 1.5 % between the real and estimated volumes was demonstrated, and this can be seen as an acceptable level of accuracy for the method.

The accuracy of CTV depends on different parameters of CT images, such as a slice thickness, field of view, matrix size, and the boundary criteria used to define the area of interest. These factors are important and should be taken into account when measurements are performed. In this study the slice thickness was 1.0 mm without intervening gaps, the field of
view was 25 cm, the matrix size 512, and the boundary criteria were not a big problem in the nasal cavities, because the contrasts between the different tissues were so intensive.

With CTV, various factors hindering the acoustic rhinometry measurements can be conveniently avoided. The areas behind the constrictions in the nasal cavities, spaces under the turbinates and osteomeatal complex, all of which cannot be distinguished reliably with acoustic rhinometry, can be reliably measured with CTV. This makes the method more accurate compared to acoustic rhinometry. This could also be one of the reasons why volumes and areas measured with CTV are constantly larger than those obtained with acoustic rhinometry. This finding contradicts the results published earlier in studies where CT/MRI is compared to acoustic rhinometry (Corey et al 1997; Hilberg et al 1993). In addition, the volumes of intranasal pathology and paranasal sinuses can also be separately measured, which is not possible with acoustic rhinometry.

Acoustic rhinometry is a rhinometric method widely used in rhinology to measure intranasal geometry. It is based on the analysis of reflected acoustic impulses. It automatically computes the cross-sectional areas and, using several integration algorithms of these area curves, it also calculates the volumes of the nasal airways. The methodologies of CTV and acoustic rhinometry were compared in Studies I-II. Acoustic rhinometry and CTV were both patient friendly and painless in clinical use. Acoustic rhinometry was rapid, cheap and easy to perform, while CTV took 6 times longer to perform than acoustic rhinometry. CTV was also at least twice as expensive as acoustic rhinometry examination. CTV also included a radiation dose to the eye region, although this was as big as that given in a routine sinonasal CT image. CTV is currently performed in the supine position and acoustic rhinometry in the upright sitting position. This may contribute to the impaired correlation between the methods when the results are compared, because earlier studies have confirmed that changes in posture contribute significantly to nasal patency, i.e., decreased nasal cavity dimensions with the chance of postures from standing to supine and to lateral positions (Kase et al 1994). Other factors which may affect the strength of the correlation between the CTV and acoustic rhinometry results are in some cases a nasal cycle and a difference between the planes of CT slices and the acoustic impulse pathway used for volumetric calculations.

Djupesland and Rotnes have investigated the effects of different orientation plans in their recent work with a stereolithographic plastic model determined from HRCT scans. They noted that the accuracy of
acoustic rhinometry depended on the orientation of the planes used to calculate the dimensions (Djupesland and Rotnes 2001). In the future, it would be important to try to automatize this seeking of planes from scans where the cross-sectional areas are smallest and then compare the results obtained with acoustic rhinometry on living subjects. This will be one of the future projects of the present author.

Accuracy of acoustic rhinometry

In Study III, comparable values of volumes and cross-sectional areas were measured between acoustic rhinometry and CTV. Despite some methodological problems, a strong, statistically significant linear correlation and agreement between the volumes was found in the anterior and middle parts of the nasal cavity up to 40 mm. In the posterior part the correlation was only moderate, and the deviation of these results was relatively wide. The accuracy of single points presenting MCAs was much poorer compared to the volumes.

Mayhew and O’Flynn have also been reported a strong correlation with cross-sectional areas measured on sections from a cadaver head (Mayhew and O'Flynn 1993). Other studies comparing dimensions in living patients derived from CT/MRI scans with manual volumetric analysis and acoustic rhinometry have reported a good correlation in the anterior parts of the nasal cavities, but a much poorer correlation further posterior. The definitions for anterior and posterior parts in these studies have, however, been very vague (Gilain et al 1997; Hilberg et al 1993). Results similar to those obtained in this study were reported in a study made by Corey who concluded that measurements correlated strongly up to 40 mm when acoustic rhinometry was compared to MRI-based manually edited volumes (Corey et al 1997).

CT-based analyses involve some basic problems, which should be recognised when this type of comparison is made. The first problem is the difference between the axis of the CT images used in the measurements and the real acoustic pathway in the nasal cavity. This difference in planes automatically leads to differences in cross-sectional areas and volumes obtained with the methods. The difference is caused by linear cross-sections in the antero-posterior measurements used in CT and the non-linear cross-
sections used in acoustic rhinometry. A recent study has shown that when
the acoustically derived dimensions are compared with those calculated
from the true areas perpendicular to the presumed course of the acoustic
pathway, the accuracy of acoustic rhinometry compared with imaging
modalities increases (Djupesland and Rotnes 2001). This factor contributes
to errors, especially in cross-sectional areas and volumes in the posterior
parts of the nasal cavities, where the acoustic pathway does not follow the
orientation of the planes traditionally used in CT/MRI images. The second
problem is the paranasal sinuses, which may significantly contribute to the
acoustically determined areas in the posterior parts of the nasal cavity and
nasopharynx. However, in healthy subjects the sheltered location of the
meatal ostium and paranasal sinuses behind the middle turbinate protects
against sound energy loss to the sinus ostium. In Study III, where about half
of the nasal cavities measured were operated on, including the middle
meatal ostium and anterior ethmoidal sinuses, this could be a significant
factor, probably causing errors in the results for the posterior parts of the
nasal cavities. In nasal models the influence of sound loss to the sinuses has
already been reported in acoustic rhinometry measurements (Hilberg and
Pedersen 1996). The third problem is possible leakage of acoustic sound
pulses, to a contralateral nasal cavity or oropharynx during the
measurements, which also leads to errors in interpreting results. This is not
usually a major factor, because it can be seen easily from printed area-
distance curves. The fourth problem, which should be noted when the
results are compared, is that the measurement of both the volume beyond a
constricted area in the nasal cavity and the area of the constriction may be
associated with systemic errors. This error has been calculated in nasal
models and may be as much as 10 % (Hamilton et al 1995). This cannot be
observed in CT-based measurements, which are more accurate in this
respect. On the other hand, the image window used in CT measurements
may eventually attain some degree of significance in volumetric
measurements and confound the results. Wider image window levels lead to
inaccurate increase and narrower image window levels to inaccurate
decrease in the volume measurements.

For future validation studies it would be most important that these
problematic factors should be observed, especially the progression of the
acoustic pathway. Imaging modalities with software capable of calculating
the intranasal dimensions parallel to the acoustic impulse would be the
answer to currently unanswered questions.
Reference ranges for rhinometric measurements

The normal nose measured with different diagnostic tests is a much sought-after definition. However, it is a very problematic definition, because normality may mean typical, ideal or it may vary a lot between normal individuals. Therefore, in Study IV rhinometric data was presented as a range of values, reference ranges encompassing 95% of the cohort population obtained with acoustic rhinometry, rhinomanometry and nPEF meter. Earlier studies have shown that intranasal geometry and nasal function are clearly dependent on many different factors such, as age, race (Morgan et al 1995) and subjective sensation of normal nose. Differences in subjective sensations means that some individuals can have almost total obstruction of the nose without any sensation of nasal obstruction in the individual itself (Grymer 2000). These factors make the definition of reference ranges even more challenging.

Reference ranges analogous with the Study IV have not been described earlier in the rhinometric literature and therefore direct comparison of the results with other studies was difficult. Numerous separately measured rhinometric reference values can be found in the literature. In an analysis of data collected from different studies median MCA obtained with acoustic rhinometry was 0.52 cm², and with a 2.5 percentile limit on minimum value 0.32 cm² (Hilberg and Pedersen 2000). In Study IV the median was 0.68 cm² and the reference range 0.26 – 2.39 cm². Hilberg and Pedersen’s results are an analysis of different studies, which means that the criteria are heterogeneous regarding the definition of a normal nose. It can be defined by normal rhinoscopy, subjective sensation or in some studies both criteria may be used. In Study IV normality was defined by medical history including the individual’s subjective sensation and clinical rhinological examination. All subjects with nasal obstruction or intranasal pathology were excluded. Despite these differences in the study settings, the lower limit for MCA seems to be quite similar between the materials.

The problem with NCV comparisons is that almost every author in the literature has defined the area where the volume has been measured in a different way. Corey et al. used the volume 0 – 60 mm, Marguez-Dorsch et al. used 0 – 70 mm, Grymer et al. also used total volume 0 – 70 mm etc (Corey et al 1998; Grymer et al 1991; Marquez-Dorsch 1996). Probably one of the reasons for this is that regions are apparently based on the printout settings of the software used at that time by the authors. In Study IV, which
was performed before the emergence of SCAR guidelines the NCV was measured between 10 and 40 mm. The latest recommendations regarding measurements are that NCV 0 – 50 mm or for mucosal changes 20 – 50 mm is calculated (Djupesland and Rotnes 2001; Hilberg and Pedersen 2000). These recommendations are good, because they are in accordance with the modern technical development, and the anatomical, physiological, and clinical understanding of the nose. In future studies it would be most valuable to perform controlled studies according to these guidelines. However, the author has not so far observed any reference ranges for these volume areas in the literature.

The comparison of reference ranges for NAR also seems to be complicated, because various mathematical models and units have been used in study settings. Many laboratories appear to use they own limits for normal and abnormal values, which is actually a good practice for clinical work. However, studies conducted according to ISCR guidelines can also be found and compared. Gammert et al. defined the upper normal limit for total NAR at 150 Pa pressure to be less than 450 Pa/l/s in non-decongested nose and 300 Pa/l/s in decongested nose (Gammer 1988). Jessen in his work used the Broms method at radius 200 and concluded that the reference interval in decongested nose was from 100 to 500 Pa/l/s (Jessen 1989), and Sipilä and his co-workers in turn defined values at 150 Pa pressure and using Broms method at radius 200. He determined that NAR in decongested nose was normal if unilateral NAR was less than 300 Pa/l/s at 150 Pa and less than 200 Pa/l/s at radius 200. The total NAR was normal if it was less than 150 Pa/l/s at 150 Pa pressure and less than 90 Pa/l/s at radius 200. However, he preferred to use Broms’ method instead of recordings at 150 Pa pressure, because the pressure gradient was not measurable in 62 % of the patients at 150 Pa (Sipila et al 1992). These limits are defined after decongestion based on the fact that decongestion reduces the NAR by 20-55 % in healthy subjects, and should be used when the skeletal status of the nose is evaluated (Cole 1980; Sipilä 1991).

Non-decongested values are more seldom seen in the literature, but for the mucosal changes they are important. Jones reported the reference interval for non-decongested noses at 150 Pa pressure to be 200 – 600 Pa/l/s (Jones 1987) and Sipilä presented average total NAR at radius 200 in non-decongested nose to be 91.6 ± 45.5 Pa/l/s (Sipilä 1991). In Study IV, the reference range for unilateral inspiratory NAR at radius 200 was 10.3 – 382.1 Pa/l/s, while for the total inspiratory NAR at radius 200 it was 7.0 – 107.5 Pa/l/s. In this study the reference range for inspiratory NAR is lower
than those published earlier in the literature. The reasons for this may be due to differences in exclusion criteria and technical arrangements. In these results, unilateral or total inspiratory NAR is the most often used parameter and naturally has the greatest clinical value. Expiratory values are seldom reported, but in some cases it may be important to examine these values, too. In Study IV, inspiratory values are reported and in addition expiratory NAR parameters are presented in non-decongested nose. The intranasal dimensions are likely to differ significantly between the congested and decongested state (Cole 1980). Most studies in the literature prefer the use of some kind of decongestants in measurements when skeletal structures are studied, and to avoid the “nasal cycle”. The understanding of this unusual phenomenon is still very confused and there is a very little evidence for any true periodicity. The alternating “nasal cycle” occurs only in 13 % of individuals as reported by Gilbert and Rosenwasser according to their most stringent criteria. Moreover, the periodicity of this cycle is seen to vary between the individuals and between tests in the same individuals. The duration of a cycle range was 0.8 – 5.5 hours (Gilbert 1987). Intranasal decongestants were not used because the aim of Studies IV-VI was to examine the rhinometric methods in patients with disorders mostly affecting the nasal and paranasal mucosa. For more complete reference ranges, it would have been important to ascertain the decongested values, too.

Studies in nPEF rates in healthy subjects are a rarity. Normal values for nPEF rates have been presented without any calculations of reference intervals. The range for the non-decongested noses was 325 – 379 l/min and 371 – 413 l/min in decongested noses (Wihl and Malm 1988). In Study IV, the reference range for nPEF rates was 175 – 520 l/min. The difference is remarkable, and understandable, because the material in the earlier study included only 12 subjects versus 249 subjects in Study IV.

The wide variation in rhinometric results can be seen in various studies. It is partly due to the mingling of different age and races, different methods used in studies and different study settings. This may indicate that local reference ranges may be of some value before the national and international reference ranges have been defined according to committee guidelines for these rhinometric methods.
Rhinometric methods in clinics

In Studies V-VI, acoustic rhinometry, rhinomanometry, CTV (VI), nPEF (V), and VAS was tested in patients with acute upper respiratory infection (V), and in chronic sinusitis patients before and after endoscopic sinus surgery (VI). It was clearly seen that the rhinometric methods sensitively measured the mucosal changes in intranasal geometry and function during the pathological changes in the nasal cavities. Moreover in Study IV, the significant changes in intranasal dimensions and function obtained with these rhinometric methods were clearly seen between the non-smokers and smoking healthy subjects. Unfortunately the number of smoking cases was too low to permit any strong conclusions about the effect of smoking on intranasal dimensions.

The comparative studies between the different rhinometric methods and parameters were somewhat surprising. Statistically significant correlations ($p < 0.05$) between methods were found, but an absence of clinical correlation ($r < 0.40$) was noted in all aspects of comparison between different methods (Dunn 1995). Parameters within one and the same method in turn correlated strongly with $r > 0.90$ and $p < 0.05$ (MCA vs. NCV and expiratory NAR vs. inspiratory NAR). At any rate an interesting trend was anyhow when agreement between parameters in healthy and pathological noses was compared. Agreement between the methods seemed to be better in noses where some pathology was seen. This could be an object for further research, or then mere coincidence. Earlier studies show very confusing results and conclusions. Some studies reports a clear correlation between acoustic rhinometry and rhinomanometry (Scadding et al 1994), other results comparing acoustic rhinometry, rhinomanometry, and VAS yield opposite results, but still conclude that acoustic rhinometry and rhinomanometry correlate to each other with $r = -0.27$ (Tomkinson 1996a), and finally Silkoff found a good correlation between acoustic rhinometry and rhinomanometry in the right side of the nasal cavities, but no correlation in the left side or bilateral comparison between the methods (Silkoff et al 1999).

The choice of the rhinometric method for use in clinics is an important question. Acoustic rhinometry is a static measurement method of intranasal geometry. Rhinomanometry in turn is a dynamic test of NAR. Both methods are accurate, easy to perform, cheap, rapid, portable and patient friendly. The accuracy of acoustic rhinometry is good, but the technique has
some technical limitations, which should be noted in measurements. Rhinomanometry is also a sensitive, specific and highly reproducible method with some pitfalls. Nasal PEF is also an easy, rapid, cheap and patient friendly method, but the information obtained with the method is modest. CTV is not so practical as needed in every day clinical work, but in the future with more technological advances it will hopefully become one of the methods in routine use.

The values obtained with these different rhinometric methods from healthy and pathological noses are mutually consistent, but the analysis of values revealed no statistically significant clinical agreement between them. Each method improves the diagnosis of the rhinological patient, but it seems that none of the methods is a substitute for the other and the different methods may be complementary. For clinical work the author himself personally recommends the simultaneous use of acoustic rhinometry and rhinomanometry in rhinological patients, such as the studies in nasal physiology, in allergic disorders, in some structural defects e.g. septal deviations and polyps, in nasal obstruction, and in studies about therapeutic effects e.g. surgery and drugs.

The future of rhinometric methods

The advances in computer technology may increase the validity of classical rhinometric measurements such as acoustic rhinometry and rhinomanometry in parts of the nasal cavities and nasopharynx, which with present knowledge yield unreliable measurement results. Advanced imaging modalities may give us the greatest technological improvements in the immediate future. Double spiral computer tomography scanners make it possible to take images faster, in several planes simultaneously, and give us higher resolution. With the help of image fusion it is possible to perform dynamic imaging. Movable CT/MRI scanners can also make it possible to measure patients in a same position simultaneously with CTV and acoustic rhinometry, thereby diminishing the source of errors when comparisons between the methods are made. CTV and similar methods can be used more often in rhinometric measurements and in evaluation studies in the future, when the techniques and facilities will be faster, cheaper and more easily available.
CONCLUSIONS

1. Computed tomography volumetry based on semi-automatic segmentation of CT images was tested in nasal airways, and concluded to be an accurate method for rhinometric measurements. CTV was compared to acoustic rhinometry, and it was concluded that the method was more accurate than acoustic rhinometry and suitable for the evaluation of acoustic rhinometry, but still unpractical for everyday clinical work.

2. The accuracy of acoustic rhinometry was good up to 40 mm, and further posterior the accuracy decreased but remained moderate. The accuracy of minimum cross-sectional areas were much poorer compared to the volumes.

3. A table of the reference ranges for acoustic rhinometry, rhinomanometry and nasal PEF was produced for the clinical work of a local laboratory.

4. The results obtained with acoustic rhinometry, rhinomanometry, nasal PEF, and visual analogue scale are mutually consistent, but the analysis of values did not verify any statistically significant agreement between them. The methods can be seen as mutually complementary.
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