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Consensus report on acoustic rhinometry and rhinomanometry*

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(Standardisation Committee on Objective Assessment of the Nasal Airway, I.R.S. and E.R.S.)

SUMMARY

With respect to acoustic rhinometry, new elements concern the problems related to the interpretation of the minimal cross-sectional area, and the presentation of a protocol for a multinational study, which aims to define a normal nose. Also, the previously issued recommendations for standardisation for technical specifications and standard operating procedures are briefly reviewed.

For rhinomanometry, new insights into the field of fluid dynamics are highlighted, as well as their repercussion on more recent graphical representations for active anterior rhinomanometry such as four phases rhinomanometry and resistometry.

For acoustic rhinometry as well as rhinomanometry, a more stringent standardisation of decongestive procedures is suggested.

Key words: acoustic rhinometry, rhinomanometry, fluid mechanics, guidelines, standardisation

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OBJECTIVES OF THE PRESENT CONSENSUS CONFERENCE

The previous meeting of the Standardisation Committee on Objective Assessment of the Nasal Airway was held as long ago as 1983 (February 1983, Brussels). Since then, numerous and important developments have been made. However, during the previous E.R.S. Meetings a lack of progress in the mutual recognition of several recording techniques and standardisation issues became apparent. The present Consensus Conference therefore tries to resolve all controversies and aims to achieve a mutual understanding of clinicians, surgeons, scientists and manufacturers.

METHODOLOGY

A draft of the proceedings was sent to the participants of the Consensus Conference. Each of them was asked to review and comment this draft. For those topics where a full consensus is lacking, the individual comments are given.

I) ACOUSTIC RHINOMETRY

Moderator: Ole Hilberg

Acoustic rhinometry allows the determination of the cross-sectional area of the nasal cavity as a function of the distance into the nasal cavity. As such, acoustic rhinometry provides a two-dimensional picture of the nasal cavity. The method is based on a comparison/analysis of the amplitude (representative for the area) of sound waves as reflections by the nasal cavity of an incident sound wave, and this as a function of time (representative for the distance into the nasal cavity). Methodological and clinical aspects, as well as recommendations for technical specifications and standard operating procedures have previously been outlined [1,2].

In non-decongested noses, three deflections or minimum notches on the area-distance curve are noted. The narrowest part of the nasal cavity is usually situated within a distance of 3 cm from the nares. Two minima have been described in this region [3]. One deflection reflects the nasal valve (I-notch representing the Isthmus nasi), the other the anterior end of the inferior turbinate (C-notch representing the head of the inferior turbinate or Concha) [4]. The first notch may, in fact, be artefactual [5]. One of the two first minimum areas is often the absolute minimum of the curve. In some subjects the minimal cross-sectional area (MCA) corresponds to the nasal valve, while in others it corresponds with the head of the inferior turbinate. Comparison of the location of the MCA in the same subject before and after decongestion may be helpful to determine whether the MCA corresponds to the nasal valve or the head of the inferior turbinate. [With decongestion, the forward displacement of a MCA corresponding to the head of the inferior turbinate is more pronounced than the forward displacement of a MCA corresponding to the nasal valve (Figure 1)]. The origin of the third deflection is less clear: probably it corresponds to the head of the middle turbinate. Areas measured in the posterior part of the nasal cavity may be affected by the openings to the paranasal sinuses (especially the maxillary sinuses) and by sound loss to the nasopharynx. [The change in the size of the sinus ostia during decongestion may significantly increase the effect on the area-distance curve behind this point. This may influence the evaluation of the nasopharynx, but may on the other hand be a measure of the ostium function.] The posterior part of the nasal cavity affects the feeling of obstruction to a minor degree and nasal obstruction is generally located *in* the anterior part of the nasal cavity [1] (see below: clinical use of variables obtained by rhinometry).

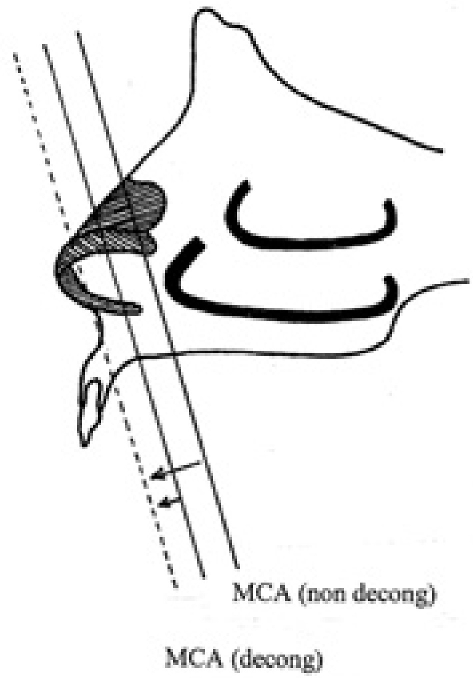


Figure 1. Displacement of the minimal cross-sectional area during decongestion.

Standardisation of technique

Standard nose

A standard nose is a plastic model with circular areas that provide an area-distance function based on a recording of a normal nose. These standard nose values have been published before [1]. All manufacturers of rhinometry equipment use the same standard nose (some companies provide a standard nose, while others have provisions for an automated use of a standard nose). This standard nose is intended for testing and optimising the equipment. It allows, for instance, repeatability tests (see hereafter) and training of new operators. However, this standard nose is not intended as a normal nose for comparison of the data of an individual patient. A future multinational study will try to define such a normal nose (OH@mil.au.dk). The area-distance curve of the standard nose should provide a straight line for about the first 4 cm (4.472 cm) if the equipment is functioning properly. A straight tube is also used for similar purposes: with a properly functioning apparatus, a straight line should be obtained too. The use of such a straight tube and a standard nose are not redundant. According to the manufacturers, both should be used for a more precise calibration.

Testing repeatability and accuracy

Procedures for evaluation of accuracy and repeatability of the measurements in the standard nose have been presented before [1] and remain unchanged. Repeatability and accuracy are both applied to selected parameters such as nasal cavity volumes in the distances 0-5 cm and 2-5 cm (see hereafter) and the minimal cross-sectional area (see above/hereafter). The repeatability of measurements can be described by a single number (Mean SD/Mean % = 1.15%) as the mean coefficient of variation of 10 measurements over the entire distance of the standard nose. However, the coefficient of variation increases considerably with the distance. The overall accuracy can also be illustrated by a single number (0.022 cm^2) as the mean accuracy for measurements over the entire distance of the standard nose. The accuracy too decreases as the distance from the beginning of the standard nose/nasal cavity increases. Decreasing the variability and increasing the accuracy can improve measurements. This may be obtained by making an average of single rapidly made measurements, eventually with the use of curve rejection algorithms. External noise, changes in the environmental temperature and humidity, changes of position of the sound tube, sound leaks at the nostril, pressure changes due to swallowing and breathing, may all have an influence on the reproducibility and accuracy. Particularly temperature and humidity changes necessitate daily calibrations with the standard nose.

Publication of results

Descriptions of acoustic rhinometry results for publication have been addressed before [1]. At the least, the nasal cavity volume in the distance from 0 to 5 cm (for mucosal changes the volume 2-5 cm) from the nostril should be given together with the two first minimum areas and their distances from the nostril within the first 5 cm.

Checking the equipment and making measurements

A trained operator should perform quality control of the equipment. A control with the standard nose as well as the straight tube has to be done daily. Calibration checks should be done weekly. Step cavity and straight tube testing should always be done after corrections and interventions on the equipment. Installation of new software versions requires full testing and comparison with the old software.

Obtaining accurate and reproducible measurements is dependent of a broader setting of conditions. Equipment performance has to be defined and validated. Quality control has to be performed by a trained technician under the supervision of a medical doctor. Measurements have to be assessed for reproducibility and acceptance and are to be compared with reference values for interpretation. Clinical assessment of the obtained data together with a continuous and overall quality evaluation is of course important. References for the different recommendations for standard operating procedures and controlling of the environmental conditions can be found elsewhere [1]. From a technical point of view, measurement equipment can be considered reliable. The actual focus should therefore be on proper training of the users of rhinometry equipment. [Unpublished studies have shown a three- to eight-fold difference in the variability of repeated measurement performed by trained and untrained examiners [6].

Coupling between the nose and the equipment

Nosepieces, as coupling devices between the nose and the equipment, have to provide a sufficient acoustic seal without disturbing the anatomy. Separate (left and right) anatomical nose adaptors (of appropriate size) probably provide better results than measurements obtained with a common adaptor for both sides. The use of a head support is felt to be impractical with respect to the positioning of the measuring tube. Nosepieces should either be disposable or treated with appropriate hygienic precautions in order to avoid transmission of infectious diseases.

Information provided by the manufacturers

Recommendations for the manufacturers with respect to the provision of information about accuracy and repeatability, resolution, calibration and adjustment procedures, maintenance and hygienic precautions, environmental and safety standards remain unchanged [1].

Clinical use of variables obtained by acoustic rhinometry

The total area-distance curve as obtained with acoustic rhinometry contains information about the geometry of the nasal cavity. Therefore, the best way to evaluate results is to consider the entire curve rather than single values.

With respect to the assessment of nasal obstruction, some areas in the nasal cavity are more related to the feeling of obstruction than others (the feeling of nasal obstruction is not a mere question of cross-sectional area's or of the ratio between laminar and turbulent flow alone: see discussion with fluid dynamics and rhinomanometry). Nasal obstruction is mostly located in the anterior part of the nasal cavity. In acoustic rhinometry, the narrowest part of the nasal cavity is usually situated within a distance of 30 mm from the nares. Two minima have been described in this region (see above). These two first minimum areas and their distances from the nostrils should be measured, together with the nasal cavity volume in the distance from 0 to

5 cm from the nostril. Nasal patency shows spontaneous variations but is also influenced by exercise and pathological conditions. Allergic subjects out of the pollen season have for instance more congested and more sensitive nasal mucosa than nonallergic subjects [7].

For mucosal changes the volume 2-5 cms seems to be an important variable.

Information about the sinuses and especially the ostia connecting them with the nasal cavity may be found in the areas between 5 and 10 cm (see above).

The most reactive region of the nasal cavity on nasal challenge is illustrated by the variable of the cross-sectional area at the anterior end of the inferior turbinate (where the maximum congestive capacity of the nasal mucosa is located), 3.3 cm from the nostril. Nasal challenge tests are felt to be useful in the presence of occupational health problems and as a way to motivate patients following a desentisation programme (in the presence of nasal hyper reactivity, nasal provocation tests with histamine are less useful due to an important overlap between normal test subjects and patients; furthermore correlation between nasal and bronchial provocation test is lacking. [G. Scadding remarks that a nasal provocation test with lysine-aspirin may be a safer alternative to oral challenges in ASA patients [8]].

With nasal provocation test, both sides should be challenged in order to account for the effects of the nasal cycle. The most reactive side is used for further data processing. Determination of nasal volumes (2-5 cm and/or 0-5cm) is felt to be more appropriate than the use of minimal cross-sectional areas. Measurements should be obtained 5 minutes (15 minutes is felt to be too much time-consuming) after nasal provocation.

Acoustic rhinometry can be used to measure changes in the congestion of the mucosa and record skeletal abnormalities. Decongestion of the mucosa should be done in a standardised way. A α_2 mimetic (e.g. oxymetathazoline or xylomethazoline; 2 sprays of 50 µg in each nostril; repeated after 5 minutes with a single spray) is administered in two steps. A one step approach is felt to be insufficient (>< Djupesland) in the presence of important nasal congestion. Measurements should be obtained at approximately 15-30 minutes after the full effect of the drug is achieved.

II) RHINOMANOMETRY

Moderator: Peter AR Clement

Rhinomanometry is the measurement of the pressure encountered by air passing through the nasal cavity [9]. Active anterior rhinomanometry (the patient is actively breathing through one nasal cavity while the narinochoanal pressure difference is assessed in the contralateral nasal cavity) is the most commonly used method of rhinomanometry. Passive anterior rhinomanometry (the pressure is measured for each nasal cavity separately at a given airflow of 250 cm^3/sec) is fast but less accurate than both other types of rhinomanometry and is mainly used for nasal provocation tests. Active posterior rhinomanometry (the choanal pressure is measured via a tube placed in the back of the mouth while the airflow is measured for both nasal cavities simultaneously) is frequently hampered by gag and suction reflexes and is therefore limited to physiological studies or assessment of the nasal patency in the presence of septal perforations or if one nasal cavity is completely obstructed.

With active posterior rhinomanometry not only the narinochoanal pressure difference but also the pressure difference in the nasopharynx is measured. Because the latter depends essentially on the position of the soft palate, the measurement result can differ to a great extent.

PHYSICS AND FLUID MECHANICS

For a better understanding of the different aspects of rhinomanometry, it is useful to have some elementary knowledge of the ventilation mechanisms of the nose. The mechanics of nasal ventilation are based on the laws of fluid dynamics and have been outlined in a previous publication [10].

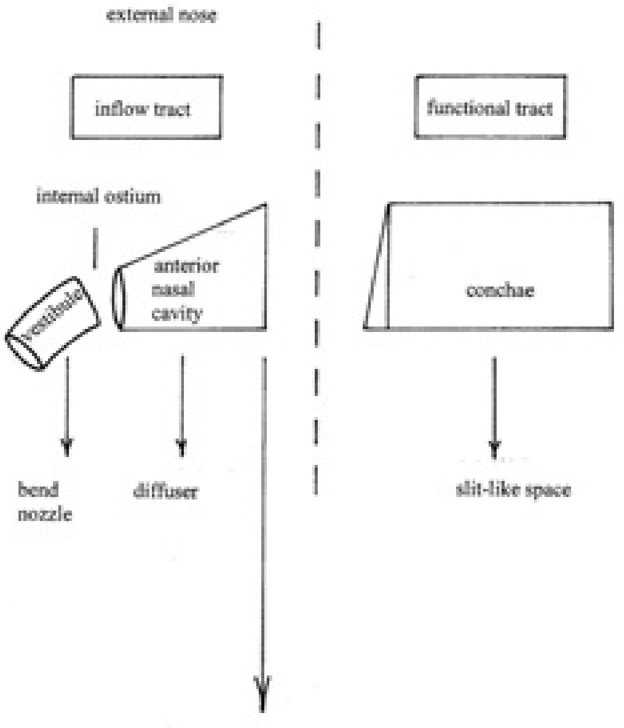
In order to achieve a sufficient contact between the air and the nasal mucosa during respiration, several preconditions can be identified:

- Low airway resistance
- Large contact surface
- Flow distribution around the whole surface
- Narrow stream channels
- Well balanced turbulence behaviour

During a normal nasal cycle, one nasal cavity is assumed to be in a "working phase", while the opposite cavity is in a "resting phase" which allows a restoration of the mucosa. The associated subjective feelings of nasal patency/obstruction as well as the objective assessments of nasal patency are not merely a question of the nasal resistance. The occurrence of turbulences is of importance too.

In order to understand the generation of turbulence by the nose, fluid dynamic experiments have been performed by means of anatomically exact models [11]. Such transparent models are made on the basis of a cast of the nose, obtained under general anaesthesia before surgery by filling the nasal cavity with easily removable silicon rubber. These models are run through with water and streamlines are visualized by traces of dye. The experiments show that both laminar (with a sharp border between dye and water) and turbulent flow (with mingled dye and water) occur in the nose. Pure laminar flow is only found at a very low flow-velocity. At about 20 cm^3/s first turbulence can be observed. With increasing flow-velocity, turbulence increases and laminar flow behaviour decreases ("transition range"). At about 500 cm^3/s (individually different: from 400 to >1000 cm^3/s) purely turbulent flow is observed. Turbulence is a precondition for the exchange between the flowing air and the mucosa (important for the respiratory function and for olfaction). The fluid dynamic experiments have

Figure 2a. Inflow- and functional tract



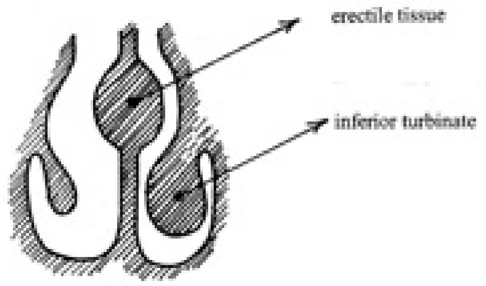


Figure 2b. Cross-section at the end of the diffuser. Turbulences are more likely to occur in the decongested than the non-decongested nasal cavity.

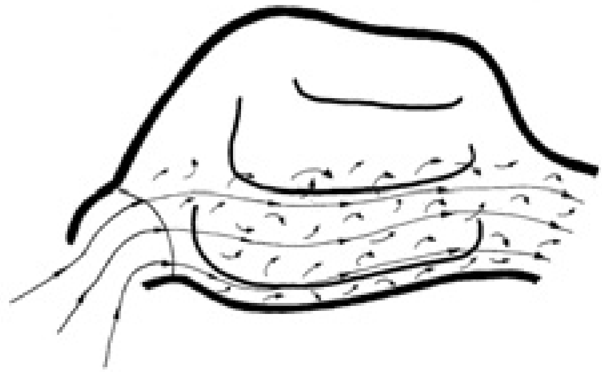


Figure 2c. With a nasolabial angle between 90-100°, the inspired air is redirected from inferior-lateral into the region of the turbinates.

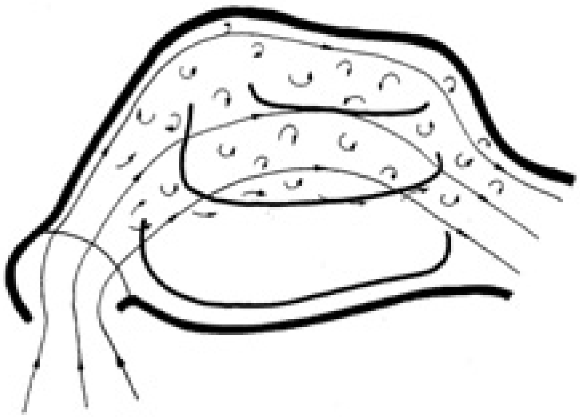


Figure 2d. With a nasolabial angle < 90°, the airstream is directed during inspiration in the upper part of the nasal cavity, while the lower part is not ventilated.

demonstrated that the nose can be divided in three areas: the inflow area, the functional area and the outflow area (Figure 2a). In inspiratory direction the inflow area comprises the nasal vestibule (which is configured as a bent nozzle) and the anterior nasal cavity (which acts as a diffuser). The concavely curved, narrow internal ostium is situated between the vestibule and the anterior nasal cavity. The functional area includes the region of turbinates and is shaped like a slit-like space. The outflow area consists of the posterior cavum, the choana and the nasopharynx. Because of the nozzle effect of the nasal vestibule laminar flow is seen at the level of the vestibule and internal ostium. The bent shape of the vestibule effects a redirection of the inspired air from inferior-lateral into the region of turbinates. The correct bearing of the nasal vestibule to the cavum is of great importance. This is the case if the nasolabial angle is 90-100° (Figure 2c). A downward rotated vestibule (nasolabial angle <90°) directs the air stream in the upper part of the cavum while not ventilating the lower part (Figure 2d). An upward-rotated vestibule (nasolabial angle >100°) guides the air through the lower cavum. The concavely curved shape of the internal ostium effects a diverging of streamlines, comparable with light passing through a concave lens. This contributes to the distribution of air over the entire surface within the functional area. In the anterior nasal cavity, the cross-sectional area increases. It is this increase in cross-sectional area that generates turbulence. The larger the increase in cross-sectional area, the more turbulent the airflow becomes. Coronal CT-scans at the end of the diffuser illustrate topographical details that may be of importance for the generation and regulation of turbulences (Figure 2b). Variations in the increase in cross-sectional areas (and with this in the creation of turbulence) can be achieved by alterations of swelling of the erectile tissue situated on the nasal septum, and the head of the inferior turbinate. For the respiratory function, well-balanced turbulent behaviour is a precondition for sufficient contact of all flowing air particles with the mucosa. Decongestants can -by widening the cross-sectional area between the inferior turbinate and the erectile tissue of the nasal septum- give rise to a more turbulent airflow. Turbulence is therefore probably not the sole reason for a subjective feeling

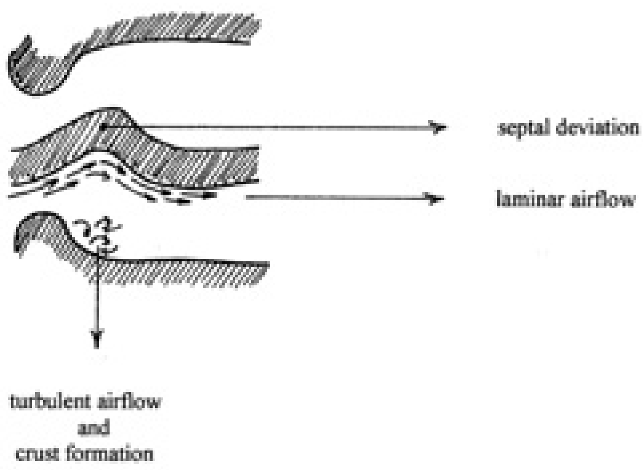


Figure 3. Nasal septal deviation seen from above.

of nasal obstruction. It is more likely that the ratio between laminar and turbulent flow is of importance. The velocity as well as the loss of acceleration of the airflow can also contribute to nasal obstruction [12].

The findings of several authors with respect to discrepancies between the subjective feelings and objective measurements as well as the influence on the subjective feeling of nasal patency by thermo receptors situated in the nasal vestibule [13] have been reviewed elsewhere [14].

Turbulence and so-called "dead spaces" (enlarged areas in the slit-like space, where slowly rotating eddies arise) are also responsible for nasal crusting. In the presence of a nasal septal deviation, nasal crusts develop contralateral to the actual septal deviation, in the enlarged part of the nose: while the airflow is still laminar and forward flowing in the immediate proximity of the (concave part of the) nasal septum, near the surface of lateral nasal wall the airflow becomes a slowly rotating eddy (Figure 3). The eddy and turbulent flow behaviour lead to a drying of the mucus and to an increased sedimentation of particles, causing crusts. In inspiration the air leaves the functional area passing the posterior cavum (nozzle: decrease of turbulence), the choana (convex curved opening: converging of streamlines) and the nasopharynx (bend: redirection of streamlines in the lower airways).

During expiration similar findings as shown in Figure 2c can be seen. The inflow area during expiration corresponds to the outflow area during inspiration but it now runs in the inverse direction. The nasopharynx is shaped and acts as a bend: redirecting the air, coming from below to the functional area (region of turbinates). A nozzle effect is not necessary, because the air comes as laminar from the lower airways. The choana in expiration is a concave curved opening with a function comparable to that of the internal nasal ostium in inspiration. During expiration, the posterior part of the cavum (meatus nasopharyngeus) with its increase in cross-sectional area is shaped and acts as a diffuser, which creates turbulence, important for the retrieval of warmth and humidity within the functional area.

In expiration, the region of turbinates corresponds with the functional area as well. In this breathing phase, the warm and wet air gives energy and moisture back to the mucosa. Therefore sufficient contact with the mucosa is also a precondition. During expiration the anterior cavum acts as diffuser, reducing turbulence. The internal ostium with its convex shape leads to a converging of the streamlines and the bent vestibule directs the air downwards, so that the exhaled air leaves the nose in a narrow beam and at high velocity [15].

When the airflow increases, Reynold's number will increase beyond a critical value and the laminar flow will suddenly change into turbulent flow with boundary layer separation. In circular pipes, the critical value of Reynold's number will be 2320 [10]. The anterior part of the nasal cavity, behind the internal ostium has, however, a configuration with an increasing cross-sectional area. This part of the nose can be considered as a diffuser. Turbulences are generated, independent of the "opening angle" (large angle- high degree of turbulence, narrow angle - low degree of turbulence). The origin of turbulence within the diffuser can start near the inflow opening of the diffuser (internal ostium of the nose).

Due to the irregular nature of the nasal cavity, "boundary layer separation" is likely to happen for Reynold's numbers not much higher than 2300. The Reynold's number is estimated to be between 500 and 2000, and hence the nasal airflow is predominantly laminar. However, according to older publications of Solomon (quoted in Clement and Hirsch [10]), the Reynold's number is 1335 at the level of the choanae and 3220 at each mucocutaneous junction. For Hirsch one overall Reynold's number (for each individual person) for the nasal cavity is perhaps sufficient. The square resistance coefficient R_S ($R_S = \Delta p/V^{\circ 2}$) decreases with the square power in the majority of patients with increasing airflow, which is contrary to what can be expected for laminar flow [10]. Probably the classical rules for pipes are not valid due to much localised energy losses: inspir- and expiratory flow behaves as an oscillating (see below) rather than constant airstream; irregular, slot-like nasal passages instead of a circular circumference; narrowings and diaphragms (ostium internum, choanae); curved rather than straight airflow are all responsible for additional pressure drops [10]. With respect to the nature of the nasal flow, previous studies into the field of fluid dynamics such as those conducted by Fischer and Masing, used models that didn't allow separate analyses of the different parts of the nose. Althaus et al. used models based on 3D reconstructions of CT scans of the nose together with photographic and laser techniques in order to visualise moving particles. These experimental settings allow the determination of the ratio of laminar/ turbulent flow as well as the assessment of the velocity distribution for the whole nose.

MATHEMATICAL MODELS

A $\Delta p/V^{\circ}$ recording has the drawback of being difficult to turn

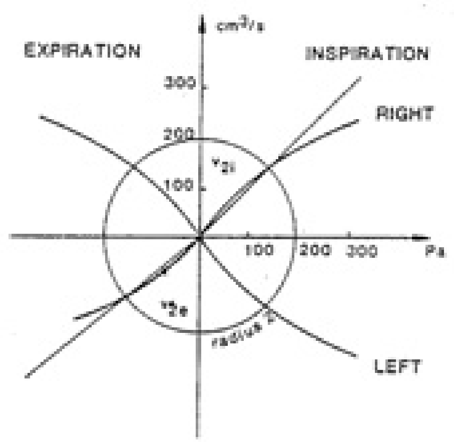


Figure 4. Broms' mathematical model (active anterior rhinomanometry): v_{2e} is the angle that the recording of the right nasal cavity makes with the flow axis at radius 2 during inspiration (right upper quadrant): v_{2i} is the angle that the recording of the right nasal cavity makes with the flow axis at radius 2 during expiration (left lower quadrant).

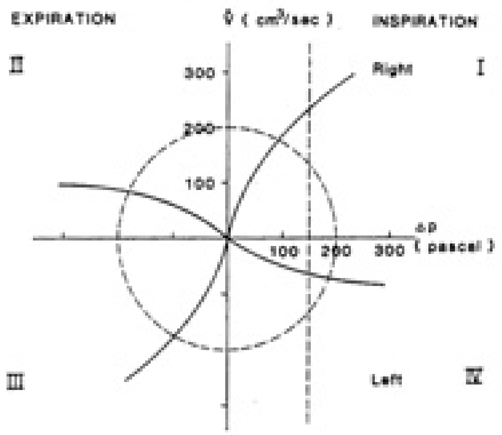


Figure 5. Mirror image technique using the four quadrants of the graph in active anterior rhinomanometry:

- inspiration: right of the flow axis
- expiration: left of the flow axis
- quadrant I-III: right nasal cavity
- quadrant IV-II: left nasal cavity
- resistance should be given at a fixed pressure of 150 Pascal or at radius 2 when using Broms' model

into numerical values and is therefore hardly usable for statistical analysis. Therefore, a mathematical description of the whole pressure flow recording would be most useful. The polynomial model of Rohrer ($\Delta p = k_1V° + k_2V°^2$) and the polar coordinate model of Broms ($v_r = v_o + cr$) (Figure 4) seem to be the best suited [16]. In the Rohrer model, $k_1V°$ represents the laminar portion of the pressure-flow relationship and $k_2V°^2$ the turbulent portion.

In Rohrers model the laminar ($k_1V°$) and turbulent part ($k_2V°^2$) is constant for all velocities. That is not true for the nose (see above). At very low flow-velocity we have laminar flow. With increasing velocity turbulence increases. At high velocity the flow is purely turbulent. Therefore, Rohrer's equation has to be modified: $\Delta p = m(V°)\, k_1V° + n(V°)\, k_2V°^2$
where under laminar conditions $m(V°) = 1$, $n(V°) = 0$,
under turbulent conditions $m(V°) = 0$, $n(V°) = 1$,
within the transition range $m(V°)$ decreases, $n(V°)$ increases.
Beside this, it makes no sense to describe the entire curve with one equation. Such an equation is surely highly sophisticated but does not provide any clinical or statistical advantage. It is an advantage if one calculates separately in the three ranges (laminar, transition, turbulent) on the basis of fluid dynamic laws, corresponding to the actual flow behaviour (as done in Rhinoresistometry: see below).

In Broms' model, v_r represents the angle that the $\Delta p/V°$ curve makes with the flow axis and that varies with the radius (r), v_o is the angle at the origin, and c is an abstract number in the equation that describes the curvature of the $\Delta p/V°$ curve.

GRAPHICAL REPRESENTATION

The "**mirror image**" (Figure 5) using the four quadrants of the graph remains the standard representation in active anterior rhinomanometry [9].

NEW DEVELOPMENTS IN RHINOMANOMETRY

A more recent and experimental development is the **four phases rhinomanometry** [17,18] (Figure 6). The participants of the present Consensus Conference agreed that the term four phases rhinomanometry is a more accurate description of this recording technique than "high resolution rhinomanometry". Four phases rhinomanometry might provide supplementary information because of the separated ascending and descending parts of the curves during inspiration and expiration. All members of the Standardisation Committee agree that it is useful to study the ascending and descending parts of the curve separately, and this with respect to movements of the lateral nasal wall of the

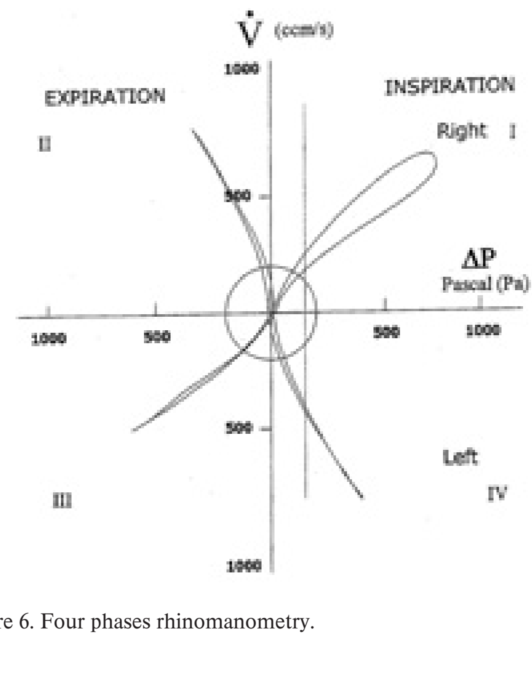


Figure 6. Four phases rhinomanometry.

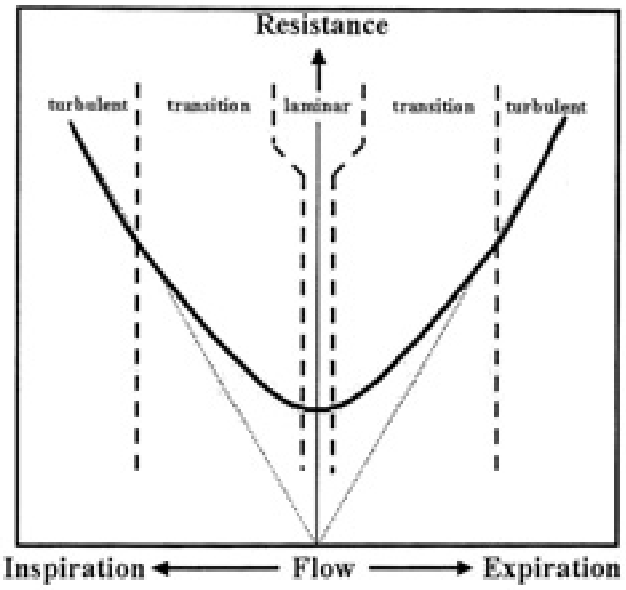


Figure 7. Rhinoresistometry.

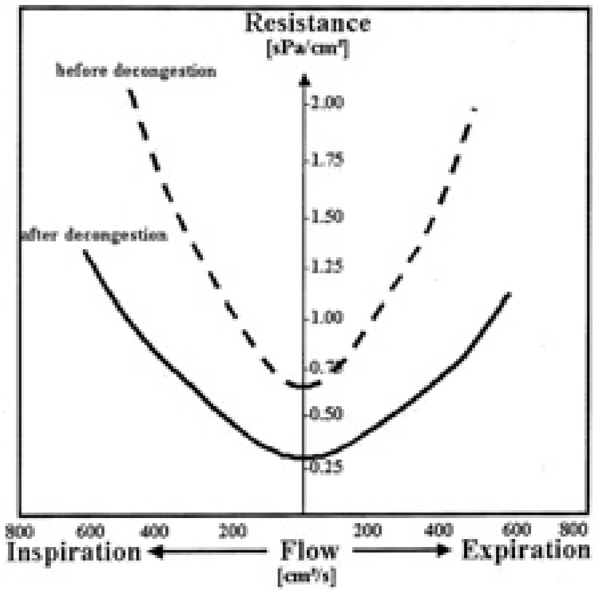


Figure 8. The influence of decongestion as seen on rhinoresistometry.

nasal vestibule during breathing. However, some members wonder how far the observed phase shift is due to the equipment used and/or the unphysiologically high pressures generated during the forced respiration necessary to obtain four phases rhinomanometry. With respect to this phase shift, the inertia of the streaming air, the elasticity of the nasal structures and the periodic nature of the nasal airflow may all be of importance. A more elaborate discussion about the fluid mechanics and mathematics related to the hysteresis/phase shifting typical for four phases rhinomanometry is available as an addendum on the Rhinology website (www.rhinologyjournal.com).

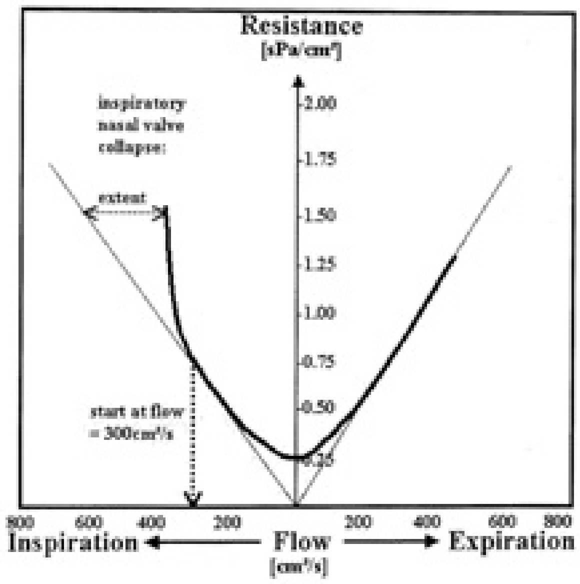


Figure 9. Pathological collapse as seen on rhinoresistometry.

Another alternative graphical representation is the **rhinoresistometry** [19] where resistance is plotted versus flow (Figure 7). With this type of representation, the range of laminar flow (course of the curve horizontal, parallel to the x-axis), the range of turbulent flow (course of the curve along a straight line which comes from zero), and the transitional range between the laminar and turbulent range, can be distinguished [$R = \Delta p/V°$; $\Delta p = 8\ \eta l\ V°/\pi r^4$ (η = dynamic viscosity, l = length of the tube, V°= flow velocity, r^4 = tube radius) stands for the laminar part; $\Delta p = \rho\lambda l V°^2 / r$ (ρ = density, λ = friction coefficient) stands for turbulent flow]. Moreover, the resistance value remains a positive number, both for inspiration and expiration. Information of clinical importance such as the differences before and after decongestion (Figure 8) and pathological collapse (diverging of the measured curve from the straight line from zero caused by a steeper course of the curve (Figure 9), are easily seen on this type of representation. From a physical point of view too, rhinoresistometry is a sound representation. As can be seen on the standard graphical representation, the flow is either truly laminar or turbulent in relatively small parts of the flow/pressure curve (Figure 10).

TECHNICAL REQUIREMENTS/SPECIFICATIONS OF EQUIPMENT

Data acquisition, pneumotachographs and pressure transducers

- For measuring flow and pressure differences similar transducers should be used. There are, however, no limitations as far as which type are to be used (diaphragm-type transducers, thermo-electric mass flow meters,…) as long as they provide linearity in a range of ± 1200 cm^3/sec and ± 1200 Pa respectively. The response time of both channels should provide a reliable measurement of flow and pressure variations up to 80 Hz. The overall error due to the apparatus should not exceed

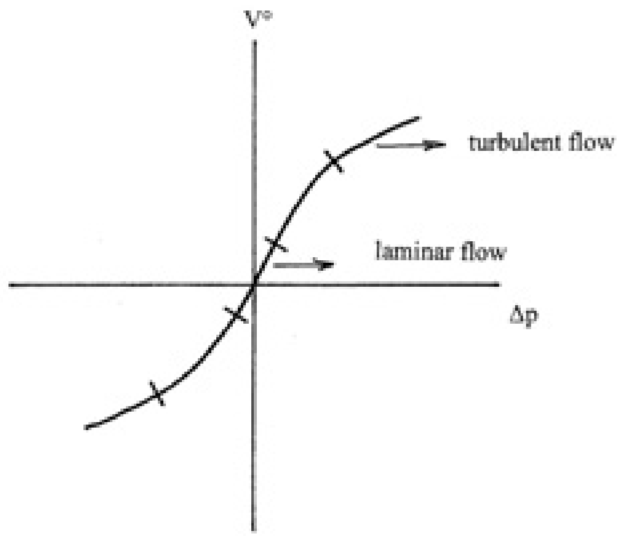


Figure 10. Standard graphical representation: truly laminar and turbulent parts of the curve.

2% FSO (Full Signal Output). The temperature and humidity range that allows correct measurements should be specified.

- Sample rate should be between 100-200 Hz. [Analysis of the frequency content of the pressure/flow signals showed, by performing a "Fast Fourier transformation", that all information was included within 100 Hz. According to the Nyquist criterion concerning data acquisition, the sample frequency was fixed on 200 Hz, which seemed a safe range for further processing [20,21].
- Depending on the type of pneumotachograph used (Fleisch or diaphragm), a resolution from 12 to 16 bits is required.
- Pressure is given in Pa, flow in cm^3/s (SI units).
- Proper data acquisition requires an on-line display in order to control for the regularity of the patient's breathing or presence of air leaks. A flow/pressure display is preferred above a flow/time display.
- Averaging should include 3-5 breaths. The optimal number of breaths depends of congruence of the curves, elimination of false breaths (without elimination of pathological breaths), purpose of the rhinomanometry, technical characteristics, availability to export the raw data to a file that can be analysed by other software.

Range for clinical purposes

Four phases rhinomanometry does extend its flow measurements to the higher pressures, in contrast to the "conventional" active anterior rhinomanometry. However, not all patients are able to reach these higher pressures. A range up to 800 Pa is therefore chosen for both forms of rhinomanometry.

Algorithms

Algorithms for calculation of derived data must be mentioned in the manual or referred to in the literature. Some manufacturers [Atmos] have provisions that allow the use of the raw flow/pressure couples. Curve fitting algorithms may not necessarily be provided.

Masks

Any type of mask that does not result in deformation of the nose and does not give leaks is acceptable. Furthermore a mask should be transparent so that deformation of the nostrils or kinking of the tubing can be excluded. When discussing rhinomanometric results, the type of mask used should always be mentioned [9]. Since the length, width and type of plastic used for the tubing may interfere with the dynamic properties of the apparatus, tubings should not be replaced except by the manufacturer. The manufacturer should mention where the reference pressure is measured in the mask.

Nasal connections

The fixation of the pressure tube should not influence the shape of the nasal entrance and should not restrict its motility during the measurement. Adhesive tape (micropore) remains therefore the gold standard. Other types of connection should be checked against this tape [9].

CALIBRATION

The basic calibration of new equipment has to be carried out by the manufacturer. A standard preformed resistor has to be a part of the equipment and should be used (for instance after total sterilisation or transportation of the system, before and after studies, etc.) by the user of the equipment to compare flow and pressure difference data with a calibration curve documented on the data file. When discrepancies (> 5% different from the original calibration) are noted, re-calibration should be performed by the manufacturer or by authorised personnel.

MEASUREMENT PROCEDURE

The measurement procedure remains unchanged with respect to the previously issued recommendations [9]. Measurements are obtained in a sitting position, after an adaptation period of 20-30 minutes. The use of decongestants and/or nasal valve dilatators as well as previous exercise should be mentioned on the graph. Decongestion of the nasal mucosa should be done in the same standardised way as mentioned above with the acoustic rhinometry.

HYGIENIC REQUIRMENTS

Any part of the system, which can be contaminated either by contact with the patient or by the expired air, must be sterilised according to general hygienic procedures or must be replaced by disposable parts.

CLINICAL RELEVANCE OF DIFFERENT VARIABLES

Different values are under consideration, particularly with respect to the determination of normal values. Normal values are very much dependent on the inclusion and exclusion criteria used to select a reference normal population. Furthermore,

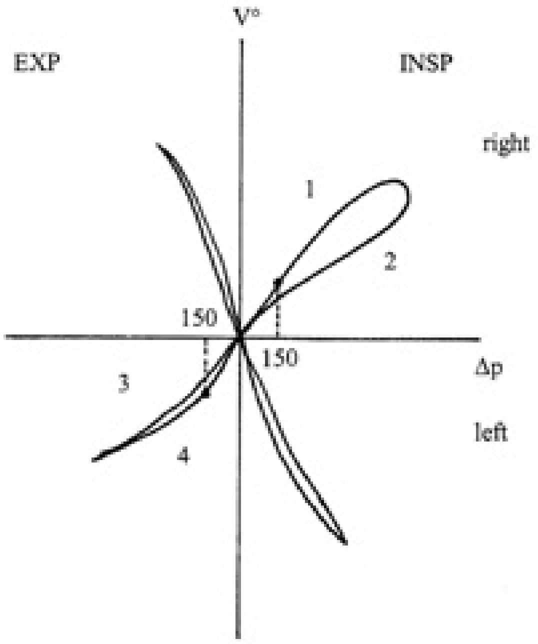


Figure 11. Four phases rhinomanometry: assessment of the flow at 150 Pa in order to determine the resistance.

the recorded data should follow a normal distribution (measurements before and after decongestion, uni- and bilateral data do not always follow the same distribution. Flow data are for instance more normally distributed than resistance data).

Resistance

Resistance is calculated according to the formula R = Δp/V° or according to the Broms' model: (resistance at radius 2) R_2. The total nasal resistance is derived by the formula Rt = $R_l.R_r/R_l+R_r$. Although these formulas are not completely correct from a physical point of view, they are suitable for clinical practice. The resistance can be calculated at different pressures (75, 100 and 150 Pa; Committee Meeting, Amsterdam 1988). In pathological conditions a reference pressure of 150 Pa can be reached easily by every patient. In physiologic studies, however, or if for whatever reason the pressure level of 150 Pa cannot be reached, the lower nasal pressures of 75 and 100 Pa can be used but should be mentioned. Resistance is however routinely expressed as the resistance determined at 150 Pa on the inspiratory part of the rhinomanometry. For the four phases rhinomanometry, resistance is determined for phase 1 (ascending inspiratory phase) and phase 4 (descending expiratory phase) of the four loop rhinomanometry (Figure 11) by using the "highest possible flow" at a pressure of 150 Pa [the ascending inspiratory and the descending expiratory curve parts are much more consistent and reproducible].

<u>For rhinoresistometry, the numerical value for the resistance is calculated at a flow of 250 cm^3/s.</u>

<u>Other single variables</u>

- k_1 and k_2 coefficient of Rohrer's model, λ coefficient and hydraulic diameter according to Mlynski-Korabljew (see above).
- Coefficient of acceleration change [12, 22]
- Maximum flow or maximum peak flow point (depending of lung function), peak flow resistance.

<u>Variables using more than one measuring point</u>

- Resistance increase, flow percentage increase [23]
- Coefficient of nasal resistance [24]
- Surface under tracing [12, 22, 25]
- Work per minute, work coefficient [26]
- Nasal quotient [27]
- Lateralistion percentage [28]

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On the website: www.rhinologyjournal.com an Addendum to this article can be found. This addendum contains an extensive description of the four phases of rhinometry. Also on the website are available the consensus reports on acoustic rhinometry from 1984 and 2000; both by Clement et al.