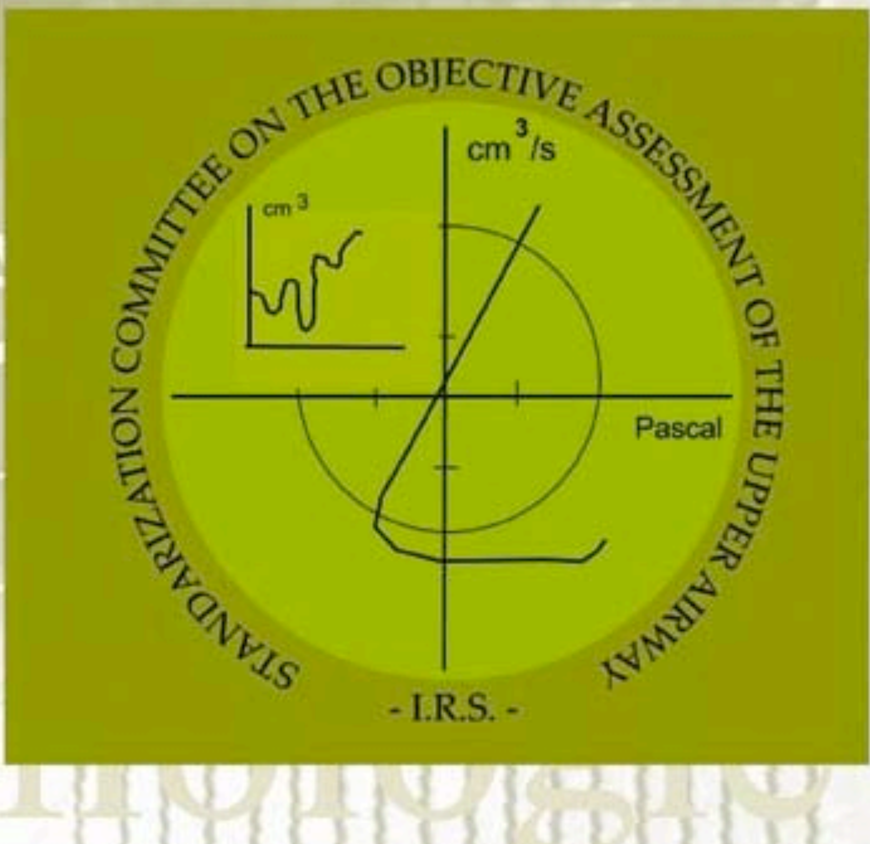
RHINOLOGY
SUPPLEMENT 21

4-Phase-Rhinomanometry
Basics and Practice 2010

Editors: Klaus Vogt, Alfredo A. Jalowayski, on behalf of the Standardization Committee on the Objective Assessment of the Upper Airway



4-Phase-Rhinomanometry Basics and Practice 2010

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Preface

Since you cannot determine function by observation alone, objective tests are welcome in medicine in general and in rhinology specifically were few functional tests exist and most are never used. Active anterior rhinomanometry using the 4-phase-rhinomanometry forwarded by Vogt and Jalowayski and a bevy of contributing authors is a welcome addition to the rhinologic literature. Having worked with rhinomanometry at Mayo Clinic since the early 1970's, I have witnessed the scientific ferment that allows accurate reproducible studies of the nasal airway, which are now possible for research and patient care. This is an important work for the modern rhinologist to study and absorb since objective evaluations are critical for the patient who complains of nasal obstruction from surgical (post-rhinoplasty) or non surgical causes. Now with 4-phase-rhinomanometry the physician can determine nasal respiratory function objectively - and this is a huge advance for research and clinical rhinology.

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Summary

4-Phase-Rhinomanometry (4PR) - Basics and Practice 2010

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The last comprehensive publications about the theory and practice of rhinomanometry appeared more than 20 years ago. Since the 1980's, the general progress of sensor techniques, fluid physics and data processing was accompanied by the permanent work of the authors to analyze the errors of rhinomanometry and to create a fundament for a contemporary and practical method that can be used in functional diagnostics of the nasal air stream.

In this special document, the objectives and measurement principles, as well as the history of rhinomanometry are described in the first three chapters. It is pointed out, that the key parameters are not only intranasal pressure and flow, but also the factor time. The technical requirements as following from the dynamics of breathing are described.

The process of averaging of rhinomanometric data lead to a separate and time-dependent analysis of the changes of pressure and flow and implicated the introduction of the 4 breathing phases (ascending and descending curve part in inspiration and expiration) into rhinomanometry and is therefore called 4-Phase-Rhinomanometry (4PR). Chapter 4 is containing a comprehensive analysis of the practical errors, which may follow neglecting the 4 breathing phases.

The in chapter 5 described mathematical-physical concept of 4PR is based on the introduction of the terms "steady" and "unsteady" flow, in addition to the up to now used terms of laminarity and turbulence. After the derivation of the HOFFRICHTER-equation as explaining the loops around the intersection point of the x-axis and y-axis, a clinical classification of the rhinomanometric findings is given and confirmed by physical experiments with "artificial noses". Finally, testing the rhinomanometric method by CFD (Computational Fluid Dynamics), lead to the same conclusions as to the importance of 4 phases of the breathing cycle.

The precondition for the worldwide introduction of new parameters into the 4PR is a comprehensive statistical analysis. The disadvantages of the present recommended standard values are described in chapter 6. Following previous studies in 5800 cases, the parameters Vertex Resistance (VR), Effective Resistance (Reff) and their logarithmic transformations have been investigated in 1580 rhinograms of different degrees of obstructions, also including the correlations to a VAS. It could be confirmed, that the parameters VR and Reff after logarithmic transformation, have a significant and high correlation to the sensation of obstruction. The new clinical classification of obstruction and conductance of the nose is proposed in Table 1 for Caucasian noses.

Table 1. Clinical classification of obstruction and conductance for Causcasian noses.

	Log10R(VR, REFF)	Obstruction, Resistance	Conductance
1	<= 0.75	very low	very high
2	0.75 - 1.00	low	high
3	1.00 - 1.25	moderate	moderate
4	1.25 - 1.50	high	low
5	> 1.50	very high	very low

Chapter 7 is dedicated to the advantages of 4PR in the functional diagnosis of nasal valve problems. Graphical as well as numerical solutions are available by the fact, that the motions of the nasal entrance as caused by the breathing process are now visible from the shape of the 4PR-curve.

Discussing practical aspects in chapter 8, the start point of proposals and discussions are the standard recommendations of the ISOANA and the results of its consensus conference in 2003. In particular the calibration processes, hygiene, the correct attachment of the pressure tube at the nostril ("tape method") and the different measurement procedures (AAR, APR), decongestion and provocation tests are extensively described.

Both the final chapters are clinical contributions from mainland China, which are of high importance because of the racial differences in nasal respiratory function. In chapter 9, tests of the assessment of normal nasal airway in adult Chinese by 4PR, rhinomanometry and acoustic rhinometry are presented. This investigation lead to the conclusion that 4PR is an important supplement to classic rhinomanometry and acoustic rhinometry, if the classification of obstruction is adapted to the higher basic resistance of the Chinese population.
Chapter 10 is dealing with 4PR and acoustic rhinometry in the functional evaluation of septal deviations and concludes, that both methods are valuable objective instruments for the evaluation of nasal obstruction.

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1. The Objective and Measurement Principles of Rhinomanometry

Klaus Vogt, Alfredo A. Jalowayski

1-1 Introduction

The beginnings of functional diagnostic rhinology go back to 1894, when Zwaardemaker [(1)] recommended holding a refrigerated metal plate under the nose during exhalation in order to estimate the degree of airflow obstruction from the relative amounts of condensed vapour. Glatzel [(2)] attempted to further quantify this method by engraving a series of equidistant arcs to the mirror. The Glatzel Mirror can occasionally be found in medical-historical collections. Further modifications of this method have been described by Jochims [(3)] in 1938 by the fixation of the condensed pattern with Gummi Arabicum.
Later, the hygrometric methods described above were replaced by methods characterizing the nasal airflow by its physical parameters of flow and pressure; thus rhinology as well as pneumonology were following methods based on physics and general fluid dynamics. Methods of estimation have now been replaced by measuring and calculation.

The goal of rhinomanometry in the past has been either:

a. to measure how much pressure is required to move a given volume of air through the nose during respiration, or
b. to determine the airflow that can pass through the nose at a given pressure.

During the transition from graphical to computerized rhinomanometry it became apparent that the most important parameter is neither the pressure nor the airflow velocity; instead, it is the relation between these two parameters, which allow us to describe more completely the physics of the nasal air stream. The basis of these relations became the accepted standard for evaluating the degree of nasal obstruction in the field of rhinology in 1984 [(4)].
During the development of computerized rhinomanometry, it was necessary to consider how pressure and flow vary during a breathing cycle. We had to analyze the dynamics of both measurement channels and to eradicate methodical errors. It became apparent, that another factor played a significant role: this factor was *time*, which had not been taken into consideration previously. Time is an important physiological factor, because it is essential that the amount of oxygen required by the body reach the lung within a period corresponding to its oxygen needs. In cases of elevated nasal obstruction, this time limit is exceeded and mouth breathing becomes necessary. For example, during vigorous exercise or physical work, this transition is physiologically predetermined. However, when a person at rest feels compelled to breathe through the mouth, this indicates that sufficient amounts of conditioned air cannot flow under those conditions through the nose. Therefore, the pressure difference between the nasal opening and the epipharynx has to be maintained for a longer period to allow the transport of sufficient oxygen to the lungs. Therefore, the diagnostic aim of 4-phase-rhinomanometry is to measure *the intranasal pressure, flow and time variables* necessary for maintaining an adequate oxygen supply through the nose.

1-2 Methodology of Rhinomanometry

The principles applied during the past few decades for measuring the relationship between pressure difference and airflow volume through the nose can be described as follows:

1-2-1 External airflow methods (Passive Rhinomanometry)
External airflow methods consist of pumping a constant, predefined amount of air through a nasal olive into or out of the nose. The resultant pressure difference generated can thus be measured. The basis of this method, so called “passive rhinomanometry”, can be traced to Kayser [(5)] in 1895, and it has been used in children, especially when active rhinomanometry testing was not possible [(6)].
Passive rhinomanometry had been the only available method used to study nasal ventilatory functions until the development of pneumotachography [(6,7)]. The passive rhinomanometry has several critical drawbacks that one should be aware when using this procedure, or when analysing and comparing data.
During passive rhinomanometry:

- The patient must hold his/her breath during the recording
- The positioning of the soft palate affects airflow resistance significantly and can be deliberately altered only by trained subjects. Airflow from an external source is often reported to cause discomfort and causes reflex movements by the soft palate
- When using alternating airflows, significant differences have been measured between the pumping and suction phases.

Passive rhinomanometry is a “one-value” method. It means that the diagnostic information is only one number/value for the pressure at a given flow level and reveals little about the dynamics of nasal airflow. When using nasal olives, the risk exists that at each “breath” the airflow is channelled in a different direction, thereby altering the geometry of the nose and affecting the measurement at each reading. Moreover, the nasal openings, including the nasal valve, cannot be assessed when nasal olives are used. This circumstance further restricts the diagnostic value of passive rhinomanometry.

The oscillatory measurement of nasal resistance assumes a special status and is likewise classified as an external airflow

procedure [8]. Here, an alternating current is superimposed on the patient's spontaneous breathing by an airflow generator. This gas flow spreads throughout the entire respiratory tract as well as into adjacent tissues. The total resistance in all respiratory passages is determined. Analogous to the theory of alternating current, the assessed resistance is a complex resistance and results from the series and parallel circuits of real, inductive and capacitive sub-resistances found in the respiratory tract.
With the oscillation method, a reference resistance Z_0 of known magnitude is connected in parallel with respiratory tract resistance Z_x. A current generator device produces an alternating current of 10Hz. The alternating pressure P produced by oscillation is measured. Analogous to the theory of alternating current, the following relationship set remains valid:

$$Z_{Ges} = \frac{\underline{P}}{\underline{V_0}}$$

$$\frac{1}{\underline{Z_0}} = \frac{1}{\underline{Z_x}} = \frac{1}{\underline{Z_{Ges}}},$$

and

$$\frac{1}{\underline{Z_0}} + \frac{1}{\underline{Z_x}} = \frac{V}{\underline{P}}$$

$\underline{z_x}$ can be calculated, where $\underline{z_0}$ and V are given and $\underline{P}$ is measured. An x-y plotter is used to make a recording in a special diagram, which depicts a graphical solution to the specific equation. Respiratory resistance value $\underline{z_x}$ can be read directly from the diagram.
Resistance in the entire respiratory tract is determined with this method. Nasal resistance can be obtained by subtracting the resistance measured through the mouth from the total resistance. It is a quick and practical method of measurement. However, the oscillation method for assessing nasal airflow resistance is a "one-value" method also, which does not permit further statements to be made about the nasal airflow pattern. No accurate result can be obtained where resistance values exceed 30 hPa/s/l. Special technical equipment (FD5/Siemens) is necessary to carry out this procedure. In the course of earlier work, we have adapted this technique to the specific requirements of rhinology [7]. Berdel and Koch [8] have recommended using this method particularly for functional diagnostics in children; however, the method is generally not widely used in rhinology.

1-2-2 Spontaneous flow method (Active Rhinomanometry)

Due to the drawbacks of external flow methods described above, a general consensus has been reached worldwide that the patient's own physiological airflow should be used for assessing nasal ventilatory functions whenever possible. Not only the natural dynamics of nasal breathing can be measured, but nasal symptoms can also be correlated to the pulmonary physiological parameters.

According to Semarak [9], these methods can even be traced to Brünings [10] and have been mentioned in the description summarized by Zwaardemaker [11]. In 1958, Semarak [9] described the first "Nasal Patency Assessment Device" that enabled simultaneous assessment of nasal respiratory flow and pressure difference between the nasal entrance and choanae.

Along with the development of functional nasal surgery in the US, Cottle [12] and his school in particular embarked on a search for an objective diagnostic procedure for assessing nasal obstruction and introduced rhinomanometry to clinical rhinology. During that time, in Germany such scholars as Masing [13], Bachmann [14], Fischer [15], von Arentsschild [16], Schumann [17] and later Eichler [18], Mlynski [19], Bachert [20], Vogt [21] and many others have contributed significantly to the development of theoretical and practical conditions for a meaningful rhinology diagnostics, particularly so for active rhinomanometry testing.

Rapid development of microelectronics within last two decades has not only made space flight possible, but it has also ensured that digital measuring technologies, originally possible only using large mainframe computers, have found their way into many areas of everyday life. In rhinomanometry, this particularly pertains to the accurate measurement of very low pressures and flow rates. Thus, new pathways have opened up in rhinology for the implementation of precise and manageable measurement technologies, which can be readapted to suit the needs of practical medicine.

Active Rhinomanometry distinguishes in turn between two measurement techniques after deriving the pressure difference between nasal entrance and choanae: the anterior and posterior methods. Active Anterior Rhinomanometry (AAR) involves closing one nostril with a measuring pressure probe, the other nostril thereby serving as an extension of the probe, while Active Posterior Rhinomanometry (APR) measures pressure difference via a tube in the mouth, with or without a mouthpiece, and held by the lips. In order to accurately measure total nasal resistance by APR, the soft palate and the tongue must be relaxed. Since pressure is deflected by the soft palate, the resistance of the anatomical structures between the oropharynx and choanae become effective in addition to the nasal resistance. Thus, rhinomanometric results obtained by AAR and APR are not always comparable. Typical examples for such differences are found in children with enlarged adenoids, in cleft palate patients and patients with nasopharyngeal fibromas or choanal polyps.

2. Technical aspects of rhinomanometry

Klaus Vogt, Wolfgang Hasse, Alfredo A. Jalowayski

2-1 Introduction

From a technical point of view, rhinomanometry is the simultaneous measurement of the volume flow through the nose and of the differential narinochoanal pressure required for the generation of this airflow and the calculation of relevant physiological parameters. Presently, this task can be completed at different quality levels by several commercially available instruments. Therefore, the following section attempts to present a summary account of currently used measuring technology, which should enable the user to critically assess the quality characteristics of different equipment.

2-2 Measurement of volume flow and differential pressure

Most rhinomanometers in practice have applied the measurement principle of pneumotachography for recording volume flow. This principle requires an introduction of a defined resistance force to the respiratory airflow. The drop in pressure caused by this hindrance is proportional to the flow velocity (Bernoulli's principle). This obstacle is generally referred to as a "spiroceptor", and various technical models of this device exist. Its classic design resembles a so-called "Fleisch′ Head" that is comprised of several metal tubes in parallel arrangement. Decrease of pressure occurring in such "heads" is linear within a specific range. Hence, the size of the spiroceptor must correspond to the anticipated flow. In prolonged testing, the spiroceptor must be warmed up to prevent water condensation inside.
So-called "lamellar spiroceptors," consisting of plastic foils arranged in parallel, have a much greater range of linearity [22,23]. The same authors have also described another device called a "diaphragm spiroceptor," where a diaphragm functions as a curtain blowing in response to airflow changes to such a degree that a linear relationship results between a decrease in pressure and airflow [23]. This formerly essential requirement for such a strictly linear relationship no longer exists today, if this non-linearity can be levelled via utilisation of appropriate analogue modules or by computer calculation. To illustrate, the information gathered by a ring-diaphragm spiroceptor is initially represented in quadratic terms with subsequent electronic root extraction of outcome data.
The critical drawback of this measurement technology is that it possesses a high degree of inaccuracy near zero values (square root of small numbers) and inevitably leads to a distortion of measurement results in this important range.

From the *hygiene* point of view, a common risk involved with the use of all pneumotachographs, and therefore all rhinomanometers based on this principle, is the fact that respiratory flow passing through the lamellae is not filtered for bacteria and appropriate and regular disinfection measures rarely take place. No publications have yet focused on this problem.

2-3 Technical problems following the dynamics of the nasal air flow

Flow sensors and sensors for measuring differential pressure must meet rigid standard requirements if the primary measurement results are to be accurate. In this respect, the precision of flow and pressure measurements is not the only important criterion. It is just as essential that the speed of the recording is adjusted to time-dependent physiological changes in respiration. The demands placed on measurement technology by the dynamics of respiration have been considered the greatest challenge in the development of rhinomanometry.

The most important parameters that can provide information about the dynamic properties of a rhinomanometer are:

- resolution
- offset drift
- gain drift
- cut-off frequency.

In this respect, resolution designates the smallest change of a signal that can still be registered. Above all, the noise level of a sensor puts restrictions on the highest possible resolution. Signal changes within the magnitude of a given noise level cannot be distinguished from general noise. These facts are well known in audiometry and are applied in the same sense in general information technology.

Primary signal resolution in digital processing of the measurements is closely related to quantization. For instance, a peak value of 5V is generated by an electromechanical pressure transducer and a serially connected primary electronic device with full-scale output (F.S.O.) of 1200 Pa. Subsequently, this signal is quantized into ± 2048 steps by a 12-bit analogue digital converter. In this case, the noise voltage of a sensor must not exceed 2.44 mV, otherwise the output is falsified.
Such a quality, to some extent comparable with CD quality sound in stereo systems, can be attained only by a small number of pressure transducers that register lower range pressures generated by a spiroceptor. The measurement of differential narinochoanal pressure in a pressure range of ± 1 kPa does not pose such technological challenges.

Sensor offset drift is a quite disagreeable characteristic, which played a significant role in early pneumotachography technology using valve amplifiers. In spite of the absence of any physiological signal, a measuring device will produce a signal. At each measurement, this offset drift is added on to the signal measured. In this respect, temperature sensitivity of a measurement system is of crucial importance. Stable sensors have an offset drift of < 1% / 10K. Superior quality sensors produce results in which offset drift is largely negligible, thereby eliminating the need for verification procedures prior to each measurement.
Gain drift, on the contrary, cannot be identified as easily as offset drift. This is a multiplicating error, which can be easily avoided by assessing and correcting the calibration of total measuring channel. Yet, it must first be identified. In modern sensor technology, which is also applied in rhinomanometry, high stability of gain is also generally a prerequisite since it permits the use of the electronic components. Therefore, various factors such as transportation, clogging of a spiroceptor or extreme atmospheric changes implement the necessity of re-calibration of the total system.

Cut-off-frequency of a sensor or, to be more precise, of the entire measuring section is an exceptionally important factor that is decisive for the quality of rhinomanometric testing. It characterises the dynamic behaviour of a measured section. At the same time, some knowledge of physics is necessary in order to understand it. Depending on the activity level, the normal breathing rate is between 0.3 and 1.0 Hz. Harmonics, however, are superimposed on this cyclical process. The results obtained in Fourier analyses prove that these harmonics can reach a frequency range of 40 Hz [24]. In practical terms of transmission technology, this means that rhinomanometric equipment should be capable of registering frequencies up to 80 Hz precisely. For a long time, though, this has been a scarcely imaginable breakthrough.

Simulation of human breathing processes to test airflow diagnostic devices can be carried out with a slowly running piston pump with a capacity of 150 ccm, which can generate sinusoidal respiration cycles. Maximal airflow velocity is assumed to be 1000 - 1200 cm^3/s. Similar airflow velocity can be generated with a piston pump having a 2.5 ccm capacity and driven with a revolution per minute (rpm) rate that is thirty times greater. It remains questionable whether the precalculated airflow value can actually be assessed. In the lower rpm range, a linear relationship develops between velocity and measured flow, whereas the indicated flow value does not increase anymore, when a specific velocity rate is reached. The cut-off frequency of the flow-channel is thus attained. In physical terms, the cut-off frequency of a sensor is reached when the signal response of measurement system is calculated to 0.707 of the real value. This corresponds to an attenuation effect of 3 dB.

Highest harmonics of the respiration frequency are found around the phase of changing of the flow direction, because the real breathing curve is more similar to a trapezoid than to a sinusoidal curve. This cannot be measured with a cut-off frequency of 0.3 Hz, but it is precisely there and this has invoked critical questions regarding the interpretation of the results.
In a series of relevant Fourier analysis tests, Mlynski [19] established that time-dependent changes in respiratory pressure and airflow values fall within the range of 40 Hz. Similar results have been reported by Versnick and Clement [24]. In general terms of transmission techniques, this implies that the cut-off frequency in a rhinomanometric system needs to be above 80 Hz.
In this respect, confusion between the terms "respiratory frequency" and "frequency content" in respiratory activity has far-reaching consequences. At the time when respiratory frequency itself is predominantly below 1 Hz (20 breaths per minute), the frequency content of respiration is determined by acceleration and deceleration processes taking place within the same inspiration. The changes occur fastest at the transition from inspiration to expiration.

Today, rhinomanometers based on the measurement principles of pneumotachography should have a cut-off frequency of about 100 Hz in the flow channel as well as in the pressure channel that no longer poses a serious technological problem. Users of such devices should be aware of the fact that the technological characteristics of a given pressure converter are not the only factors able to determine the frequency response behaviour of a rhinomanometer. Thus, caution must be exercised when modifying the length and strength parameters of the connecting tubes, which can also affect the cut-off-frequency.

The number of possible airflow measurement procedures is far greater. For anemometry, the use of thermistors, or hot wire thermal resistors, is fundamentally practicable; alternatively, airflow measurement can be carried out with Venturi tubes or Pitot tubes as used for aviation purposes. However, all of these methods are either designed for application in areas other than rhinomanometry and cannot satisfy its diagnostic requirements at a reasonable cost.

The evolution of sensor technology brought along by semiconductors has not only been instrumental in developing semiconductor-based pressure sensors but has also produced so-called "mass flow sensors" (Figure 1). These relatively new devices contain all required equipment in a miniature case, which eliminates the need for an extensive tube connecting the nasal cavity with a pressure sensor. The measurement principle consists in the microelectronic evaluation of heat transmission between two thermo-electrical measuring elements.

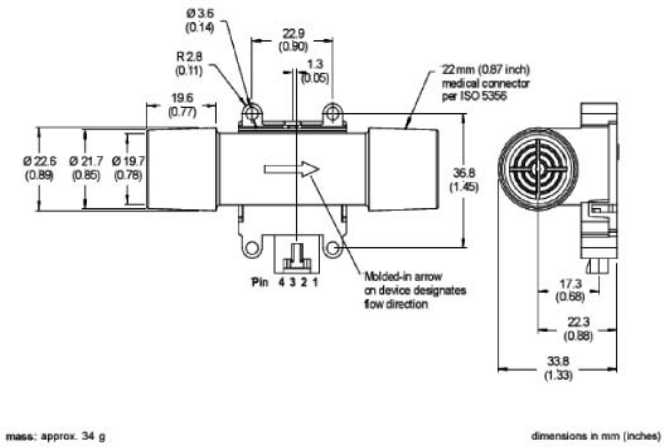


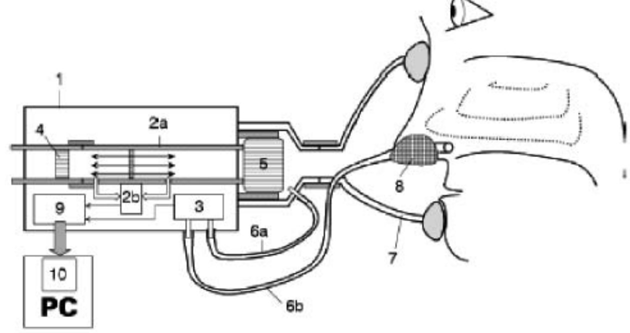
Figure 1. Mass Airflow Sensor (Datasheet from the Honeywell company).

This type of sensors offers high stability performance and compact construction. In combination with laptop computers, these devices provide a high level of mobility and open up entirely new perspectives for rhinological research and practice, especially in allergological and environmental studies. Such miniature measurement technology was first installed in the HRR 2 rhinomanometer (RhinoLab GmbH, Rendsburg, Germany). Earlier hygienic issues have been solved by implementing appropriate filtering elements.

As an example (Figure 2), such a device may consist of the following components:

1. sensor case
2. airflow sensor case
3. differential pressure sensor
4. diffusor
5. bacteria and humidity filter
6. hose connections
7. mask (sterilisable)
8. fixing element for pressure hose
9. electronic circuit
10. computer interface

(A)



(B)

Figure 2. Rhinomanometer HRR 3 (RhinoLab, Rendsburg,Germany)*. (A) Schematic picture and (B) in a set with a netbook computer.

*Footnote: RhinoLab GmbH, Friedrich-von-Flotow-Str.9, D-24768 Rendsburg, Germany, E-mail: info@rhinolab.de; www.rhinolab.de

3. Recording technology in rhinomanometry

Klaus Vogt, Wolfgang Hasse, Alfredo A. Jalowayski

3-1 Introduction

The evolution of rhinomanometry into “4-Phase-rhinomanometry” is the result of a 20-year error analysis conducted in rhinomanometric diagnostic technology, both on the side of theoretical research and technical feasibility of the procedure. While fundamental technical approaches as described above have spurred rapid developments in recording possibilities, documentation process of the obtained data and computer data interpretation remain a matter of discussion until today.

3-2 Rhinomanometry devices and set-ups

Earlier pioneers in pneumotachography and rhinomanometry recorded the results of their measurements with a so-called kymograph. Change-sensitive stylus records any deflections on a revolving drum wrapped with a sheet of soot-blackened paper. The founder of functional nasal surgery Cottle [12] aimed to incorporate into clinical rhinology the physiological findings on a relationship between nasal flow volume and the pressure required to move it. To this end, he recorded both of these parameters simultaneously on an ECG device and later evaluated them by reading the corresponding values of pressure and flow curves at the same point in time. The difficulties accompanying this methodology inevitably arise at zero points, inasmuch as accurate meter-reading is no longer possible due to curve steepness. Therefore, Cottle [12] resorted to measuring parameters at their peak values; unfortunately, though, this methodology failed to gain acceptance with time. We will return to the meaningfulness of this procedure below.
Bachmann [14] recommended recording the relationship between both variables on an x-y recorder in a direct manner – a procedure that later became the basis of today’s international standard. Representation of data interdependencies inevitably caused certain technical problems, which could be immediately discerned by every professional. First and foremost, this has to do with the fact that different elements of a measurement chain respond at different rates to changes in the measured variables. Individual elements in a given measurement setup have differing cut-off frequencies. The “cut-off frequency” of a measurement system is the highest frequency at which this system can analyse dynamic processes without loss of accuracy and to treat them as if they were static processes. A measurement system that registers two interdependent variables must align frequency response characteristics in its channels first. Precisely this was not the case with analogue x-y data representation, since the flow channel responded sluggishly due to a considerably slower transducer.

According to Figure 3, the two weakest elements in an analogue recording system were none other than the flow transducer and the x-y recorder.

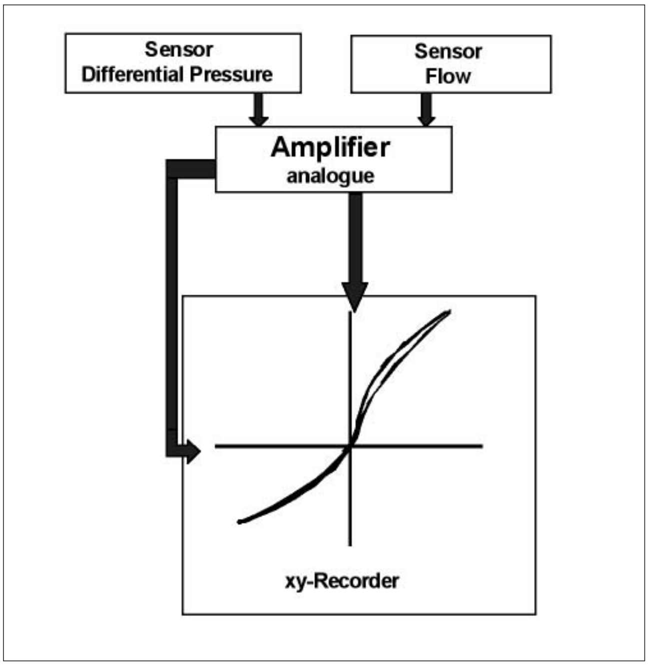


Figure 3. Analogue measurement chain in rhinomanometric procedure by Bachmann [14].

In 1980 with the aid of spacecraft engineering pressure converters and extremely short connecting hoses, a research group at the ENT department of the Charité University Hospital in Berlin, Germany; K. Vogt and team members) managed to attain a cut-off- frequency of 50 Hz in a given flow measuring section (unpublished data). Obtained data were temporarily saved in a storage oscilloscope designed for observation in an intensive care unit and subsequently read from an x-y plotter (Figures 4 and 5). This allowed recording data in the critical zero-point area with sufficient accuracy. Even at a lower diagram recording speed, however, loop curves have been detected, thus questioning the reliability of graphical curve interpretation. Besides that, it was possible to obtain truly trustworthy measurements only with cooperative patients who were able to produce a series of steady and constant breathing cycles.

Further small-scale experimenting with the aid of piston pump-generated airflow (“artificial nose”) has yielded significant findings on how various technical aspects of rhinomanometric measurement - setup can contribute to error generation, i.e., what impact can have hose dimensions, mask size, etc. on cut-off- frequency [24].

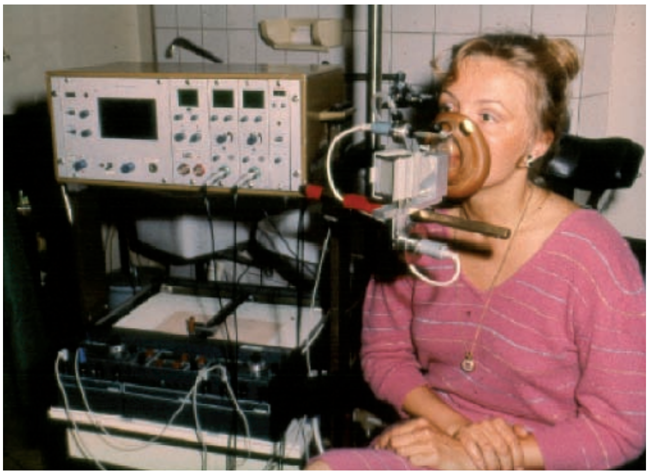


Figure 4. Rhinomanometric workstation, 1985, HNO-Clinic Charité in Berlin (ENT Department at the Charité University-Hospital). The pressure converters are mounted on a stand. Flow measurement takes place with the aid of a lamellar spiroceptor. Data are recorded using a storage oscilloscope monitor; analogue results are written by an x-y recorder.

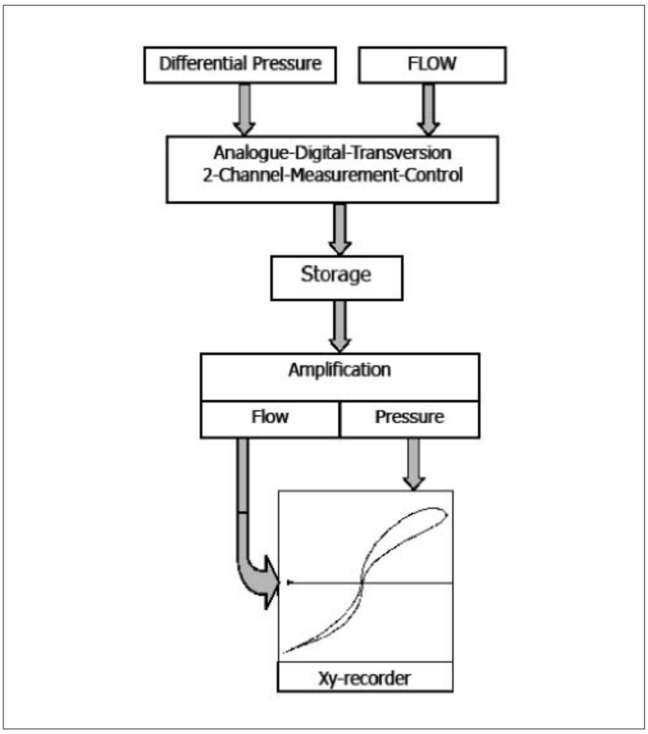


Figure 5. Hybrid system with data digitalisation, an interim stage on the route to computer-assisted rhinomanometry.

In 1982, during the ERS-Congress in Stockholm, the first results of the so-called "computer rhinomanometry" were presented. These were the interpretations of digital curves designed to produce a general mathematical model of curve progression. Similar procedures have been developed independently by research groups in East Berlin, Tbilisi and Rochester [26-28]. This development was performed on large workstations typical for that time, where measurement data were recorded in analogue form, digitally stored on magnetic tape and subsequently exported to a computer memory.

The introduction of computer technology into rhinomanometry has brought along some substantial errors attributable to direct importation of calculation methods from other scientific spheres. The initial fundamental error was the calculation of the regression between flow and pressure difference without taking notice of the individual data that arise in the process and, thereon, the analysis of an presumed function instead of the interpretation of actual measurements. On the basis of digital computation technology a new generation of microprocessor rhinomanometers has been developed. Devices of similar construction are still popular today thanks to their user-friendliness.

In the 1980s, computer technologies have also paved the way for the development of the first commercial software-based rhinomanometers, one of which was produced and released by the research group at HNO-Klinik Charité in Berlin [29]. Initially named "Carima", this system was later renamed to "Rhinodat". For over five years, it had been widely used for rhinomanometric measurements in many clinics. Different companies took over this technology after 1990 and many of those systems are still in use.

Figure 6. Carima System (1989). The first PC-controlled rhinomanometer in the world, produced by Heyer, Bad Ems, Germany. Due to a still existing problem of sensor relocation sensitivity, the case is vertically mounted onto a stand.

Despite continuous improvements in the quality and operational speed of the measurement system, the careful review of the results constantly showed the presence of loops in rhinomanometric curves, an error previously attributed to the deficiencies of the equipment. After ensuring that technical errors were excluded, the loops could only reflect phenomena as characteristic for the nasal airflow physiology. A new basic mathematical and physical concept was needed. The practical conclusion of this concept, as described in Chapter 4, was "High-Resolution Rhinomanometry". In 2003, the "International Standardization Committee on the Objective Assessment of the Nasal Airway" (ISOANA) recommended to rename this term "4-Phase-Rhinomanometry" [30].

4. Averaging in computerised rhinomanometry – the key to 4-Phase-Rhinomanometry

Klaus-Dieter Wernecke, Klaus Vogt, Alfredo A. Jalowayski

4-1 Introduction

The International Standardization Committee on Objective Assessment of the Nasal Airway (ISOANA) published recommendations of standards for rhinomanometry in 1984 [(4)]. The recommended physical units as well as parameters have been used worldwide and become an essential part of commercial rhinomanometers. These recommendations were based upon the manual graphical evaluation of rhinomanometric findings, which had been recorded on x-y recorders or plotters. In 1990, after completing extensive physical and technical studies, Vogt et al. [(19)] described the first PC-based commercial rhinomanometric system. An essential part of the software used in that system was the independent and time-related recording of data points for differential pressure and flow and the averaging of data via spline interpolation [(26)]. When introducing this procedure into computerized rhinomanometry, they observed that the increasing and decreasing phases of the airflow followed different aerodynamic conditions and that the x-y-imaging of pressure and flow, as recommended by the standards from 1984, generated loops instead of a simple curved line. At the conference held by the European Rhinologic Society in Copenhagen in 1994, Vogt and Hoffrichter proposed the term "High-Resolution Rhinomanometry" for the analysis of four different phases of breathing to underline the difference in the quality of the new procedure. During the Consensus Conference of the ISOANA in Brussels in 2003 [(30)], the committee recommended changing this term into "Four-Phase - Rhinomanometry."

After the introduction of computerized rhinomanometry into clinical practice, two different phenomena became visible in determining the shape of the loops:

1. A remarkable number of curves did not pass the intersection of the x-axis and y-axis.
2. The opening of the loops was frequently observed to be much wider in inspiration than in expiration.

The first observation is caused by the influence of the inertia of the air. The mathematical and physical interpretation will be described in detail in Chapter 5. The theoretical concept has been confirmed by many model experiments using an "artificial nose" and in recent times by Computational Fluid Dynamics (CFD). The second observation is based on the physiological behaviour of the nasal valve (see Chapter 7 for details).

4-2 Basic differences between "classic" and high-resolution rhinomanometry

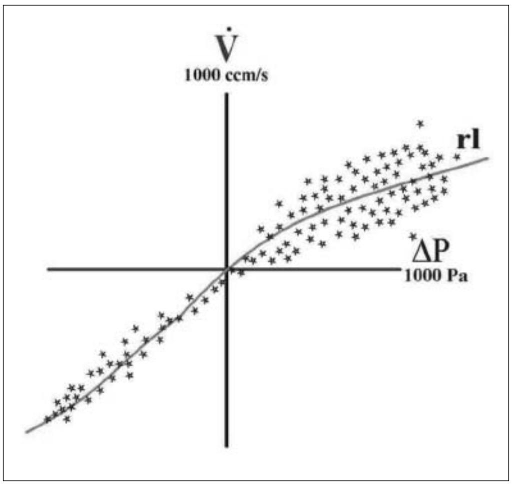


Figure 7. Averaging of rhinomanometric data by regression lines.
V = Flow; DP = Differential Pressure; rl = Regression Line

The differences between classic rhinomanometry and 4PR originate from the data acquisition process and the method of data averaging. Classic computerized rhinomanometers sequentially collect alternating values for flow and pressure and place the obtained data points in a xy-Cartesian system. Subsequently, a regression line is constructed representing the pressure-flow relationship, which starts at the origin of the axis (Figure 7).

Two important errors are generated by the above procedure that are not easily recognized by the user of these systems:

- The correlation coefficient as a parameter for the reliability of the regression line is not necessarily given in the printouts
- The rhinomanometric curve meets always the intersection point of the x-axis and y-axis

A better way of acquiring and averaging the data from different breaths is to separately and visually control the uptake of the flow and pressure data and then to construct a "representative breath" as a real-time procedure (Figure 8).
Breaths differ both in time and in the amplitude of pressure and flow recordings. The uptake process can be followed by both the patient and investigator on the screen. If the differences in length and amplitude between the single breaths are too high, the computer is instructed to discontinue the averaging procedure. The limits of such discrimination can be determined by software. After the recording process, the "representative breath" is constructed by interpolating data points up to

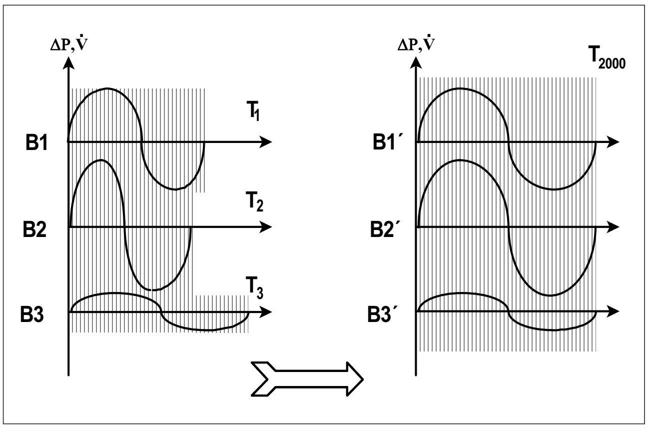


Figure 8. (A) Time-related averaging of rhinomanometric data.
Step 1: Breaths of different lengths (B1, B2, B3) are "stretched" to a standard length of 2000 data points by spline interpolation (B1′, B2′, B3′)

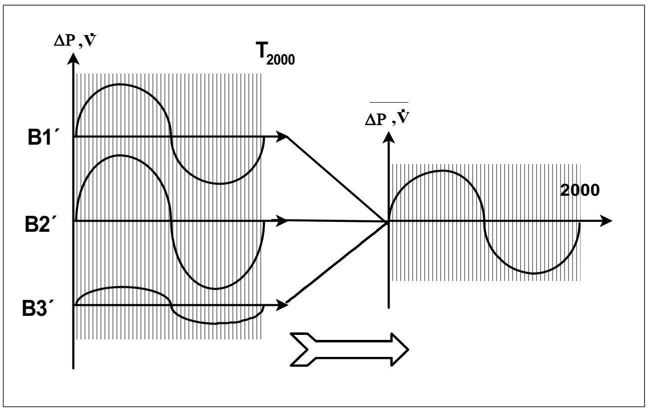


Figure 8. (B) Time-related averaging of rhinomanometric data.
Step 2: Averaging of the time-standardized breaths.

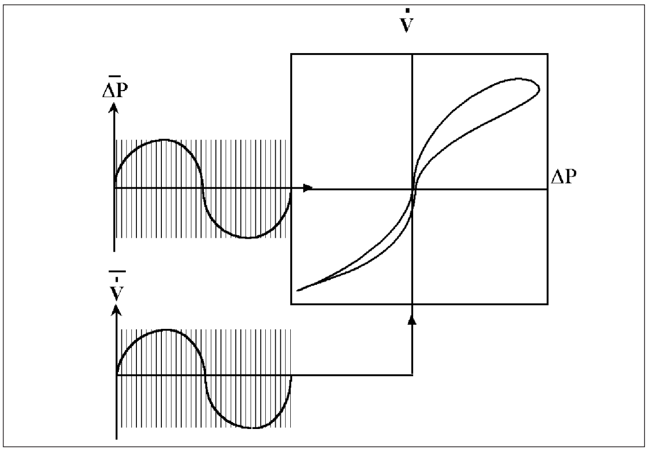


Figure 8. (C) Time-related averaging of rhinomanometric data.
Step 3: Transferring of the data for differential pressure and flow in a Cartesian System.

a unified length of 2000 points for pressure and flow and a following calculation of the arithmetic means. This time-related standardization preserves the full information of the course of pressure and flow. The pressure and flow curves are saved separately as files along with the patients identification data and

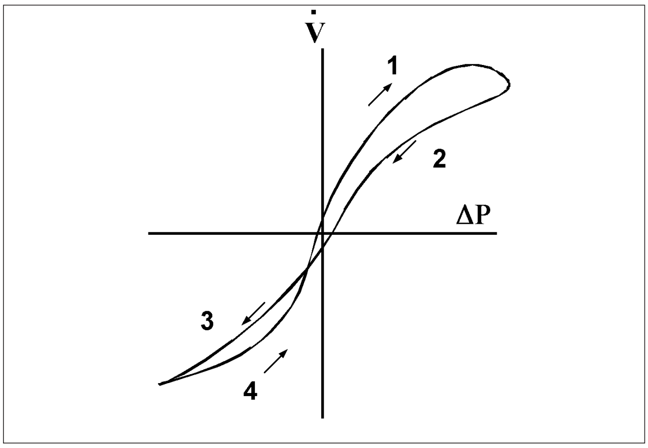


Figure 9. General shape of rhinomanometric graphs in four-phase rhinomanometry (right nasal cavity).

can be preserved for later numerical analysis of the pressure-flow relationship as well as for statistical analysis.

By using this procedure and transferring the data in a Cartesian system, a double-loop instead of a simple line is generated, which means that the pressure-flow relationship in the increasing airflow is different from the decreasing airflow. The analysis of clinical material below shows the importance of this different behaviour.

After transferring these results in a Cartesian system, the shape of Figure 9 appears.
The four phases depicted in the graph are:

<u>Phase 1</u>: Ascending inspiratory phase. The airflow is accelerated up to the inspiratory peak flow. The airflow in this phase is an exponential function of the pressure. The accelerating flow causes Bernouilli effects, which may reduce the cross-sectional area preferably at the nasal entrance by generating so-called "valve effects." Flow is instationary from the starting point of the breathing cycle up to the peak flow, but from the moment of the attained peak flow to the beginning of the decreasing phase, the airflow is stationary and almost turbulent. Under peak flow conditions the relationship between pressure and flow is linear: Depicting the relationship between the pressure-curve and the flow-curve in xt imaging shows parallel curves.

<u>Phase 2</u>: Descending inspiratory phase. The second phase is the phase from the highest inspiratory flow to the end of the inspiration. The pressure-flow relationship depends on the course of the pressure drop due to the exponential function between pressure and flow, the whirling of the airflow and the causative anatomical conditions, and on the mechanical properties of the elastic compartments determining the behaviour of the nasal entrance. When the pressure difference is zero (0), airflow may still occur if the kinetic energy of the streaming

volume is sufficient. This is the case if the shape of the nasal channel approximates a tube instead of a diaphragm. At the same pressure level as in the first phase, the flow is lower than in the ascending phase. This important fact determines the subjective feeling of obstruction.

Phase 3: Ascending expiratory phase. After the air flow changes its direction, the instationary airflow accelerates up to the peak expiratory flow. The relationship between pressure and flow is again exponential. The increasing expiratory airflow widens the flow channel to a small extent. During the short period of the expiratory peak flow, the pressure-flow-relation is again found to be linear. The variability of the pressure-flow relationship is higher than in Phase 4.

Phase 4: Descending expiratory phase. The last phase of the nasal breathing cycle is characterized by the return to resting conditions. Under physiological conditions it is followed by an expiratory break. This pause is not reproducible under the conditions of rhinomanometry.
The flow is higher than in the first expiratory phase when comparing the respective pressure levels.

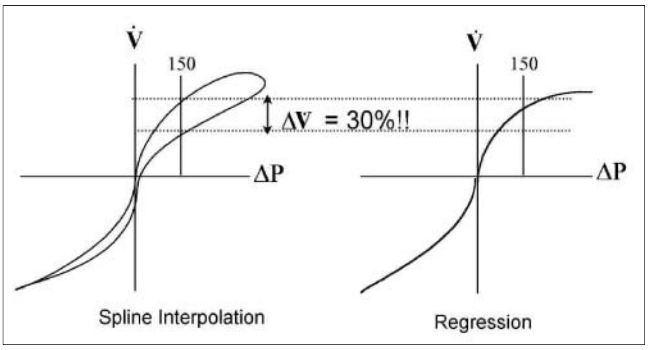


Figure 10. Incorrect averaging and depicting of results in a graph leads to severe diagnostic errors in particular in elastic deformations of the nasal air channel.

Phase 1 and Phase 4 are determined preferably by the anatomical structures of the nose. The parameters in Phase 2 and Phase 3 depend to a great extent on the generated flow.

During one nasal breathing cycle, the relationship changes between the causative narinochoanal pressure and the resulting flow. That is the reason why it is impossible to calculate or define a single pressure-flow relationship with one equation. Furthermore, the variability of the pressure-flow relationship is different within the four phases of nasal breathing.

4-3 The clinical impact of loops in rhinomanometry

Presently, users of rhinomanometry use the flow at different pressure levels as parameters of clinical importance. This is also the procedure recommended by the international standard of ISOANA. The flow at a differential pressure of 150 Pa is the main value, which is substituted by lower pressures if the 150 Pa level cannot be reached (100 Pa, 75 Pa). Other investigators are accustomed to using the linear resistance at the same pressure level, which can be calculated by dividing the pressure by flow.
If the resolution of the breathing cycle in four phases is accepted as being correct and representing the fluid dynamics of the nasal airflow, the question arises as to whether the separate analysis of the ascending and descending phases of inspiration and expiration is really of clinical importance, or whether or not averaging of the flow values for the same pressure level of the ascending and descending curve parts can be accepted for clinical purposes.

To arrive at an answer to these questions, a statistical analysis of 1377 non-classified rhinomanometric measurements of patients who visited the author (KV) because of different rhinologic problems was conducted. The material consisted of measurements of all possible degrees of nasal obstruction. A bilateral active anterior rhinomanometry before and after decongestion with xylometazoline was carried out in any case observed. The differences between the flow values at clinically important pressure levels were calculated. The mean values are noted in Table 1.

Table 1. Mean values of flow in each of the 4 breathing phases at different pressure levels.

Diff. Pressure (Pa)	−300	−250	−200	−150	−100	−75	−50	0	50	75	100	150	200	250	300
Before decongestion															
Inspiration 1									119	165	201	256	297	323	344
Inspiration 2									99	136	169	224	268	298	323
Difference %									*16.8*	*17.6*	*15.9*	*12.5*	*9.8*	*7.7*	*6.1*
Expiration 1	−330	−305	−273	−228	−169	−133	−68								
Expiration 2	−345	−324	−296	−259	−211	−180	−144								
Difference %	*4.3*	*5.9*	*7.8*	*12.0*	*19.9*	*26.1*	*52.8*								
After decongestion															
Inspiration 1				–					157	223	275	354	411	452	469
Inspiration 2									136	190	239	319	381	425	446
Difference %									*13.4*	*14.8*	*13.1*	*9.9*	*7.3*	*6.0*	*4.9*
Expiration 1	−455	−434	−392	−327	−238	−185	−102								
Expiration 2	−485	−455	−419	−365	−292	−274	−195								
Difference %	*6.2*	*4.6*	*6.4*	*10.4*	*18.5*	*32.5*	*47.7*								

Table 2. Relationship between pressure level and the number of unacceptable rhinomanometric measurements obtained by averaging the ascending and descending curve parts.

	Before decongestion		After decongestion	
	Inspiration	*Expiration*	*Inspiration*	*Expiration*
50 Pa	33%	73%	35%	65%
75 Pa	35%	45%	28%	43%
100 Pa	31%	36%	23%	26%
150 Pa	25%	23%	15%	13%
200 Pa	18%	20%	11%	7%
250 Pa	13%	8%	7%	5%
300 Pa	8%	6%	5%	4%

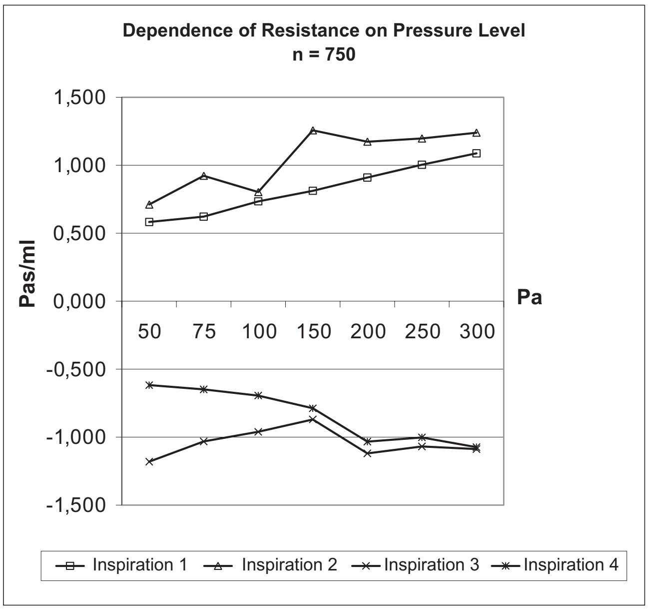
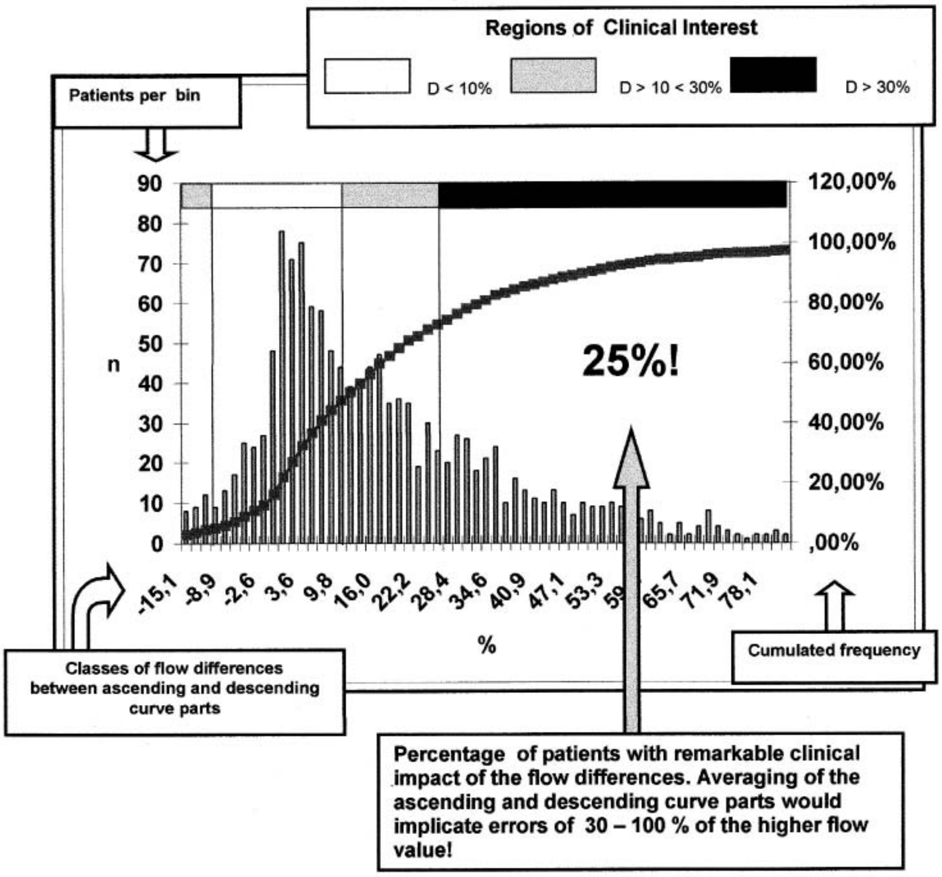


Figure 12. Relationship between pressure level and resistance values in 750 measurements in which a pressure level of 300 Pa was obtained.

The values in Table 1 and 2 show that the greatest differences between the ascending and descending phases are found at low pressure levels and that they are smaller at higher pressures. When one considers only the mean values, it could lead to the wrong conclusion. For example, a statistical mean difference of 12.5% at 150 Pa between Phase 1 and Phase 2 would not be of high clinical importance, because the deviation from the averaged value would be only 6.25%, an even acceptable figure for

Figure 11. Relationship between pressure level and the number of unacceptable rhinomanometric measurements obtained by averaging the ascending and descending curve parts.



such measurements. Therefore, much more important is the information obtained by histograms showing the statistical distribution of the differences in the entire data set. The histogram in Figure 11 shows the distribution of flow differences between the ascending and descending inspiratory curve parts at a differential pressure level of 150 Pa. Even if the range of differences between 10% and 30% were accepted, 25% of the population show flow differences higher than 30%, 10% higher than 50% difference. These differences exceed by far the criteria for a positive nasal provocation test.
Considering the pressure levels of clinical interest, the large number of measurements can be seen in which the averaging of the curve parts would produce unacceptable errors. It again becomes obvious that the greatest numbers of unacceptable results occur within the lower pressure levels.

Another disadvantage of the currently used pressure-related linear resistance is the fact that the linear resistances increase with the pressure level. It follows that a resistance given at 150 Pa cannot be compared with the resistance at 75 Pa if in a second comparative measurement the pressure level of 150 Pa cannot be reached. The relationship between resistance and pressure level is shown in Figure 12.

The main conclusion of the dependency of the linear resistance on the pressure level concerns the Polar Coordinate Model by Broms [31]. For clinical purposes, the Broms model compares the intersection points of the rhinomanometric curve at a given radius. The most frequently used radius 2 meets the x-axis (differential pressure) at 200 Pa and the y-axis (flow) at 200 ccm/s. Thus, high flow values are measured at low pressure and low flow values at high pressure. It follows, that the model is incorrect because the resistance is calculated at different pressure levels.

Summarizing the statistical data presented here, it must be concluded that neglecting the resolution of the human breath in four different phases leads to severe errors of clinical importance. The application of graphical methods for evaluating rhinomanometric curves in the modern computerized analysis of nasal breathing becomes obsolete. However, a physically and mathematically correct interpretation of the complete respiratory cycle leads to a remarkable increase in the diagnostic information, which can be derived.

5. The mathematical-physical concept of 4-phase-rhinomanometry

Hellmut Hoffrichter, Klaus Vogt, Wolfgang Althaus, Wolfgang Hasse

5-1 Introduction

After introducing the averaging procedure, described in chapter 4, which resulted in the observation of loops as the common form of the rhinomanometrical xy-curve, it became evident that it was necessary to reconsider the existing physical and mathematical concepts of rhinomanometry and the underlying flow phenomena within the nose.

The diagnostic intention of rhinomanometry is to obtain an impartial measure of the energy expended or the work performed during breathing to generate the flow of air through the nose as it is conditioned for the lungs. Except for the region of the anatomic structures of the "nasal valve", nasal breathing is about alternating ventilation of air in both directions through an *irregular* cavity with a narrowing at both ends. Rhinomanometry ostensibly measures changes in the physical parameters transnasal pressure and transnasal flow during the ventilation of the entire nasal cavity. The fluid-dynamics interpretation of several parts of this cavity by comparing it with streamed cavities within the technology becomes interesting only if one attempts to interpret an at first sight unexpected rhinomanometrical result anatomically. Previous comparisons of the nose with flow-bodies and using technical terminology that does not consider the alternate breathing through the nose may be of limited practical value.

5-2 Fluid Physics

From the standpoint of fluid physics the definitions, that are a standard element of the foundation of fluid mechanics, have so far not found their way into the fluid physiology of the nose.

When one considers the fluid dynamics, one initially distinguishes between laminar and turbulent flow. The type of flow is characterised by the Reynolds number Re, which describes the relationship between inertial and frictional forces. For Reynolds numbers up to 2300, there is normally laminar flow within a pipe. In laminar flow, there is minimal if any momentum change perpendicular to the main direction of flow. The flow is very steady and since the frictional forces are relatively high, any disturbances that occur due to obstacles encountered quickly die out. In laminar flow, the generation of detachments and eddies may also occur. If the velocity is measured at a point in the flow for an extended period, the quantity is nearly constant. The calculation of the flow rate, $\dot{V}$, through a pipe as a function of pressure change, Δp, is carried out in accordance with the Hagen-Poiseuille-Law:

$$\Delta p \; \alpha \; \dot{V} \tag{1}$$

For Reynolds numbers above 2300 in a pipe, there is normally turbulent flow and the Hagen-Poiseuille-Law loses its validity. When again measuring the velocity at a point in the flow, there are irregular, random velocity fluctuations, because the momentum develops strongly perpendicular to the main flow direction, even though the propulsive pressure force is constant. The pressure decrease no longer relates to flow in a linear fashion but rather with the flow squared:

$$\Delta p \; \alpha \; \dot{V}^2 \tag{2}$$

The pressure decrease for turbulent flows in pipes is considerably higher than for laminar flows at the same velocity. The flow through the nose goes through an irregular cavity in which there can be detachments and eddies, etc., causing yet further pressure decreases compared to the flow in a pipe. Therefore, flow in the nose can only be simulated to a limited extent using the model of flow in a pipe. Special note should be made that unlike the flow in a pipe, the flow of air in the nose is unsteady. This means that the volume of flow per unit time (volume flow rate) and the pressure difference per unit time are also a function of time, t. Bernouilli's equation, often used for the calculation of steady flows, has to be expanded to include an unsteady element:

$$\frac{\varphi}{2} v^2 + p + \int_1 \frac{\partial v}{\partial t} ds = \text{const.} \tag{3}$$

The contribution of the unsteady element depends on the amount of acceleration or deceleration over $\frac{\partial v}{\partial t}$ and on the path length l, over which the air is accelerated or decelerated.

The measurement of the flow volume rate in incompressible and steady flows is based on the principles of Bernouilli's equation for stationary flows:

$$\Delta p \; \alpha \; v^2 \tag{4}$$

For unsteady flows the relation according to the above mentioned is:

$$\Delta p \; \alpha \; v^2 - \int_1 \frac{\partial v}{\partial t} ds \tag{5}$$

At steady flows, the amount of differential pressure Δp depends on the volume flow rate and therefore can be calculated exactly. When measuring the *Δ*p in an unsteady flow, while using the formulas for stationary flow, as is commonly done, the result can be a significantly different than the true volume flow rate. The deviation from the true value depends on:

- the acceleration or deceleration $\frac{\partial v}{\partial t}$ whose variation depends strongly on the nasal flow
- and the length, *l*, of the pipe, connected upstream of the measuring system, so that an emerging trend in the flow profile may be revealed.

The measuring systems and analysis algorithms that have been used commonly up to the present are only appropriate for steady flows. There are no known easy measuring systems for unsteady flows. Therefore, one must initially rely on the common measuring systems when measuring the unsteady flows. However, for an exact and correct measurement, the analysis algorithm has to be modified, e.g. using a method that incorporates a correction of the results obtained from the steady state analysis. The correction factor must depend on the current acceleration or deceleration and the length *l* of the measuring system. The determination of the correction factor can be done, e.g. by a calibration of the steady state measuring system. An example of a method for doing this is by having a section in the measurement device blending in an unsteady but predictable flow. The variability in results due to the unsteady state applies to measurements of both laminar and turbulent flows. Therefore, a correction has to be used for both calm breathing and deeper or more rapid breathing in order to obtain a correct measurement of the volume flow rate.

The differences between steady and unsteady flow have not yet attracted any attention in rhinology, but for those experienced in fluid mechanics they are eminently important. A mathematical model, integrating the unsteady flow rate, was first described by Hoffrichter [32,33] in 1993 (see below in this chapter!)

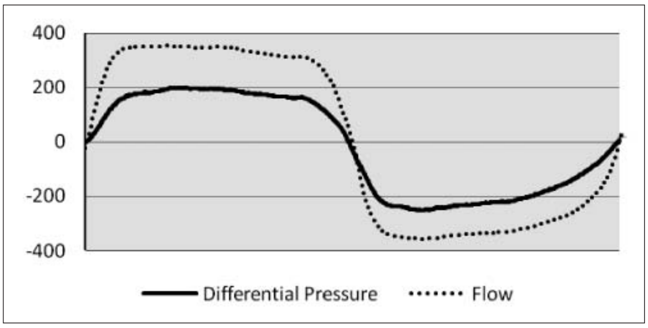


Figure 13. Breathing curve in xt-chart.

The plot of the changes in pressure and flow through the nose against time (Figure 13) - in the course of breathing in and out - shows that after a rapid increase in pressure and flow, a plateau typically occurs. The initial sharp increase-section and the transition from breathing in to breathing out are the sections of steepest acceleration, and thus are the sections with the highest frequency content. Because of the steeper temporal gradient, these sections have the highest risks of introducing errors in measurement of the flow. This questions the applicability of the current choice of measuring points in the standardised system of ISOANA. When examining these curves, which are made up of corresponding pressure and flow points for each time unit, it becomes evident that the rate of change of the pressure and the rate of change of the corresponding flow points are different particularly in the increasing and decreasing phase of the curve. Therefore, when these pressure and flow changes are plotted against each other in an xy-diagram, the result is not a simple line, but rather a loop. The xy-plot shows hysteresis behaviour, as it variously appears in nature and which is often connected with the appearance of coherent structures, e.g. swirls. Hörschler et al. [34] noted that there really is a physical reason for the hysteresis behaviour. When breathing in, the air streamlines are swirled to a greater extent than when breathing out. This implies that the same level of flow while breathing in and out corresponds to different amounts of pressure decrease thus resulting in hysteresis.

5-3 Under appropriate measuring conditions, the hysteresis curves represent a part of the flow physiology of the nose

The previously described method of averaging, introduced to rhinomanometry by Vogt and Wernecke[29] in 1990, ensures the preservation of the time-dependent information of both pressure and flow, because they are averaged first before being transferred to the x-y coordinate system. The next step is the analysis of the measured pressure-flow curve and the path of airflow in the nose.

When previous devices were used for rhinomanometry and loops were seen, various causes for the loop generation were proposed:

- Different dynamic behaviour of the pressure transducer used for flow compared with the pressure transducer used to measure differential pressure.
- Different dynamic behaviour of the actuator for the x-axis compared to the actuator for the y-axis on the xy-recorder (before computer printouts).
- Inadequate seal of the mask.
- Inappropriate dimensions of the connecting tubes between mask and flow detector or pressure transducer.
- Contaminated tubing connecting the parts of the system.

Today, dynamic high-quality pressure transducers and nearly inertia less recording technology in the form of computer screens are available. But the loops in the rhinomanometrical curves still exist. Some veteran rhinomanometer users felt that the appearance of loops meant an artefact that might be related to inferior performance by the equipment. Most equipment manufacturers have used the microprocessor technology of their product to generate an averaged function curve from the loop, which passes through the zero origin of the xy-plot. This overlooked the possibility that the loop generation reflected a physiologic phenomenon and might contain diagnostic information. It can be shown that some rhinomanometers, which display an averaged curve instead of a loop or which always display the pressure-flow curve passing through the origin, have done some manipulation of the true measured pressure and flow data and thus are not accurately displaying the changes in flow.

The many proposed models for fitting the data in the pressure-flow curve have been summarized by Pallanch[35]. These fluid dynamic equations were often based on a conduit with a length much greater than its hydraulic diameter and with minimal variations in its dimensions along its length. The nose however is an irregular cavity with significant narrowing of the dimensions of the air passage at the beginning and the end. The transnasal pressure is the result of the cumulative pressure drop at all narrowings, bendings and straight sections in the nasal airway.

5-4 Recalculation of the relationship of transnasal pressure and flow during nasal breathing[32]

These equations will be presented for breathing through an even pipe with length *1* and cross section A. There initially is non-moving air with a very low mass m in the pipe. The pressure force *F*, generated by the lungs, has a certain timeline, which will be *F*(t).

First, this pressure force pushes on the air in the entire pipe cross section and the air inside is accelerated. The first period of acceleration is Δt_1.

Accordant to the principle of linear momentum of mechanics this equation applies:

$$F\,\Delta t = m\,\Delta v = \text{const.} \tag{6}$$

Applying this equation to our example, when the pressure force F has worked for the time Δt, it has accelerated the air mass m to the speed v_l.

While the air is now accelerating through the pipe, new air rushes in and accelerates to the speed v1. But the momentum necessary for this part of the process is just $\Delta m\ v_1\ /2$, since both the newly rushing in air mass and the growing speed during Δt are only partway to reaching their maximum. The factor ½ takes into consideration this partial level toward the maximum. average value.

This initial step in the depiction of the flow is represented by the equation:

$$F(t)\Delta t_1 = (m + \Delta m/2)v_1 \tag{7}$$

The air mass Δm has now filled a distance of Δs in the pipe, resulting from the relations

$m = \square V$ (air mass = change in volume) and $V = A\ \Delta s$. (Volume = Area x length) One may also write

$$F(t)\Delta t_1 = (m + \rho A \Delta s/2)v_1 \tag{8}$$

And if one puts $\Delta s = v_1\ \Delta t_1$, then the following equation is obtained

$$F(t)\Delta t_1 = (m + \rho A v_1 \Delta t_1/2)v_1 = mv_1 + \rho A v_1^2 dt/2 \tag{9}$$

Now imagine the time course of the breath, being divided into an infinite sequence of momenta. The number of time slices, Δt, will trend toward zero and the number of momenta will approach infinity. First the notation of equation (2) has to be modified by turning the differences into differentials:

$$F(t_1)dt = mv_1 + \rho A v_1^2 dt/2 \tag{10}$$

Now imagine that the initial momentum of air has passed out of the pipe and only the momentum mv_1 is still in the pipe. The difference in the amount the momentum had increased as air entered the pipe has been blown to the outside at the opposite end of the pipe and consequently the remaining momentum, mv_1, has exactly the size necessary to accelerate the additional air rushing in. The law of conservation of momentum is not violated. As each momentum of air passes out the distal end of the pipe, the momentum already inside the pipe and the momentum that is just entering the pipe are being added:

1st Momentum: $$0 + F(t_1)dt = mv_1 + \rho A v_1^2 dt/2 \tag{11}$$

2nd Momentum: $$mv_1 + F(t_2)dt = mv_2 + \rho A v_2^2 dt/2 \tag{12}$$

3rd Momentum: $$mv_2 + F(t_3)dt = mv_3 + \rho A v_3^2 dt/2 \tag{13}$$

4th Momentum: $$mv_3 + F(t_4)dt = mv_4 + \rho A v_4^2 dt/2 \tag{14}$$

Nth Momentum: $$mv_{n-1} + F(t_n)dt = mv_n + \rho A v_n^2 dt/2 \tag{15}$$

After addition of all of these equations one gets:

$$\int F(t)dt = m\ v_n + (\rho A \int v_n^2 dt)/2 \tag{16}$$

If $F(t) = p(t)\ A$ *and* $m = \rho\ l\ A$ are set and the equation is differentiated at both sides, there finally results the differential equation:

$$p = \rho l v' + \rho v^2/2 \tag{17}$$

with $$v' = \frac{dv}{dt} \tag{18}$$

This differential equation may be rewritten with

$$\dot{V} = v * A \tag{19}$$

and

$$V = L*A \text{ (Volume = length * cross sectional area)} \tag{20}$$

to

$$\dot{V}(t)^2 = 2A^2 \Delta p / \rho - 2V d\dot{V} / dt \tag{21}$$

The graphical representation of this relationship is shown in Figure 14. A sinusoidal flow course with an amplitude of 15 ml/s through a pipe of 4 cm length and a diameter of 1,7 mm has been set. The breathing frequency amounts to 60/min. The emergence of a growing phase shift between the courses of flow and pressure is clearly recognizable.

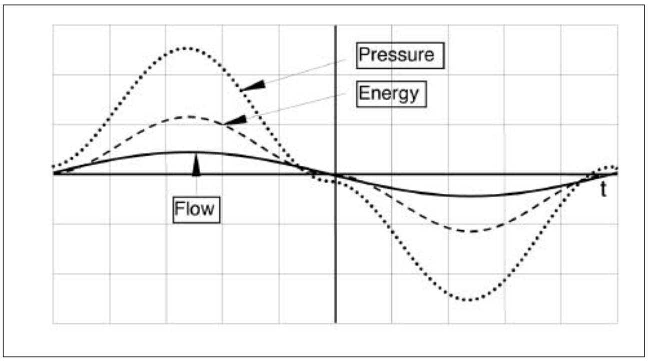


Figure 14. Flow, Pressure and Energy curve through a pipe (the scale for the Energy curve is strongly magnified).

The graphical representation of the same flow course through a pipe with steady state flow is shown in Figure 15. In this case, the unsteady part in equation (5) has been set to zero so that a steady flow results. Mathematically it can be said that the pipe length l tends to zero. It is clearly recognizable that now the phase shift is zero.

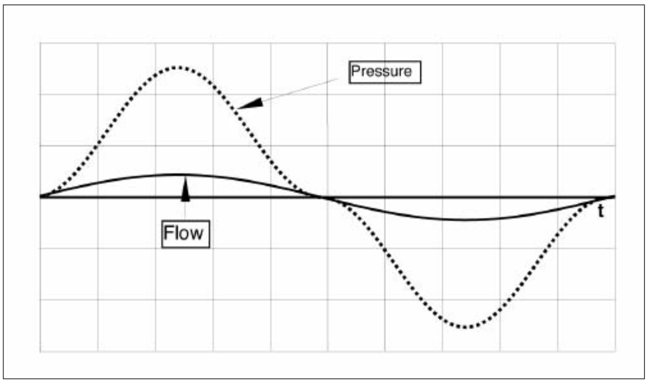


Figure 15. Flow- and Pressure curve through a pipe with steady flow.

If the pressure and flow from the time plots in Figure 14 are plotted against each other in an xy-plot, one gets Figure 16. In a similar manner, Figure 17 is obtained from the pressure and flow data in Figure 15. The graphs are numerical solutions of the differential equation (5).

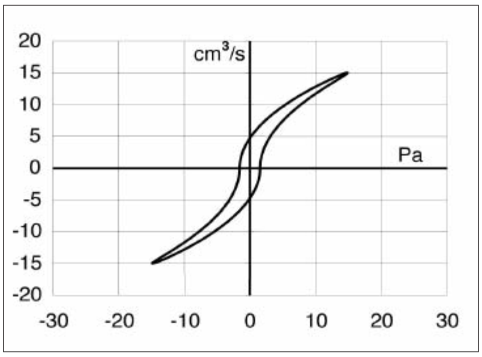


Figure 16. xy-chart of Flow and Pressure curve through a pipe of 4cm length.

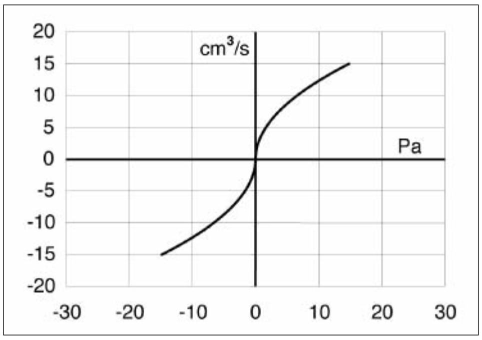


Figure 17. xy-chart of Flow and Pressure curve through a pipe of 4 cm length.

Since breathing through the nose cannot be modeled with a pipe of "length zero" but rather needs a pipe of a certain length and specific, but different, resistances for inspiration and expiration, phase shifts between pressure and volume flow rate are to be expected in a real nasal airway.

The above differential equation (6) is of the so-called Riccatical type. Therefore, solutions may only be obtained by performing a numerical simulation. The effects are interesting. Equation (5) says that the flow in the nose not only depends on the current transnasal pressure but also on its "previous history", the preceding transnasal pressures. There is a phase shift, dependent on the volume of the nose channel, between the pressure signal and the flow signal, in which the flow consistently lags behind the pressure signal. Loops do appear in the xy-plots because of this phase shift. The term $2Vd\dot{V}/dt$ may possibly reach large values. Not only does it depend on the geometric shape of the nasal airway but also to a great extent on the curved path of the airflow vectors and the frequency of breathing during testing. This results in 2 different values, of varying disparity, for the inspiratory or expiratory flow corresponding to a designated pressure. It is therefore evident that a rhinomanometrically determined nasal resistance that is calculated from the flow value at a single pressure (e. g. at 75 or 150 Pa) would not represent the 2 different measured flow values that correspond to that pressure level.

C. Hirsch, during the consensus conference in Brussels 2003 [30], stressed also the periodic nature of nasal breathing. A parameter which tells if this is of importance, is the Womersley parameter, which is defined for a cylindrical channel of radius r as follows:

$$W = r\sqrt{\omega/\nu} \qquad (22)$$

with the respiratory pulsation $\omega = 2\pi f$, the frequency f and the kinematic viscosity of the air $\nu = 15 * 10^{-6}\ m^2/s$. At higher values of the Womersley parameter (W>5 to 10) a phase shift of +90° is observed between the velocity variation and the pressure pulsation and the inertia due to the pulsating character of the flow dominates over the viscous resistance.

With a respiratory frequency of 20/min (f=1/3 and $\omega = 2\pi/3$) and the viscosity of the air $\nu = 15 * 10^{-6}\ m^2/s$, the Womersley number is $W \sim 375r \sim 1.9$ for a radius of 5mm. This is in the intermediate range, where the pulsating character of the respiratory flow is not dominating, but has a certain influence. In particular, the phase shift will be between 0° and 90°. In addition, the respiratory frequency will also enhance the effect of the elasticity of the nasal membranes through a "capacitance" effect, whereby energy is accumulated and restored periodically between the membrane and the flow. Restoration of the energy stored on deformation causes an additional phase shift of -90°.

The combined effects of flow resistance (viscosity), inertia and elasticity can be expressed by an electrical analogy, through an impedance Z, with

$$\Delta p = ZQ \qquad (23)$$

where Q is the air flow rate (m^3/s) and

$$Z = R + j\omega L + 1/j\omega X\ ;\ j = \sqrt{-1} \text{ is the imaginary unit} \qquad (24)$$

The contribution of the inertia is expressed through the inductance L and the elasticity of the membranes is taken into account by the capacitance C; with the expressions

$$R = 8Lp\nu/\pi r^4,\ C = 2\ \pi r^3/hE \text{ and } L = p\ /\ (\pi r^2) \qquad (25)$$

and h = thickness of the membrane, E = elasticity modulus of the membrane, p = density of the air. The resistance R is due to the viscosity, but will be influenced by the pulsation at the intermediate values of W~ 2. The imaginary of Z will give the phase shift. These considerations are approaching the basics of the oscillatory measurement of the nasal airstream as outlined in chapter 1.

It is important, that this impedance has also to be applied to the elastic compartments of the measuring system, which has been already discussed in the chapters above.

In 2002, A. Grzanka (personal communication) did confirm the presence of the loops at the ISANA meeting in the occasion of the conference of the European Rhinological Society in Ulm, Germany.

5-5 Graphical representation of pressure-flow relationship during alternating breathing

From these theoretical considerations as well as the results of experiments on models, it is apparent that phase shifts and loop generations are always to be expected in the rhinomanometrical result if, because of the need to create sufficient gradients to overcome an airway obstruction, a large volume of air has to be accelerated or decelerated in a short period. This is naturally the case at the transition from inspiration to expiration and vice-versa. It can also occur with fitful respiratory movements that anxious patients sometimes perform during testing with rhinomanometry. Also, a narrowing of the nasal airway e.g. caused by an anatomic convexity, can significantly increase the unsteady term in equation (5), resulting in increased loop generation.

The time sequence of the transition from one respiratory phase to the other will be presented again graphically. Figure 18 shows the time sequence of the flow in the pipe after entry of air from a much bigger reservoir. For the nose, this is equivalent to either the airspace around the external nose or the nasopharynx. At the time T0, there exists a flow caused by the lower pressure in the nasopharynx. If the pressure difference is zero at time T1, the flow direction continues as the speed of the airflow steadily decreases. At time T2, the differential pressure has changed to the opposite direction with the pressure higher in the nasopharynx. Yet the flow continues to move toward the nasopharynx briefly until time T3 when it has slowed to a stop. After time T3, the flow finally has changed to the other direction as seen at time T4.

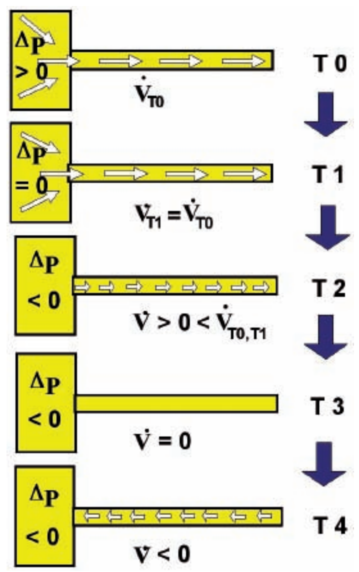


Figure 18. Fluid characteristics in a pipe at reversal of pressure direction.

What happens – with reduced viscosity and speed – is similar to the wake of a ship, still moving for a long time in a semicircular path opposite to the running direction of the ship, even when the ship is far away. In addition, the inertia of the moving air in breathing keeps it moving away from the nose after exhalation keeping us from choking on or re-breathing our own air.

The described theoretical considerations may be summarized as follows:
The generation of loops in the display of the curve data from rhinomanometry measurements is more easily seen with 4-phases- rhinomanometry than with previous rhinomanometers. The loops are due to the shape of the nasal air channel that is being measured and the alternating acceleration and deceleration of the nasal airflow.

5-6 Description of the model demonstrating the dependence of the rhinomanometric curve shape on the anatomical configuration of the flow channel

We have observed, when considering the effect of anatomical form on the nasal airway during experiments with models and in the course of our clinical examinations done with 2 different 4PR-rhinomanometers over the period of more than 10 years, that one may discern 3 different anatomical types and corresponding curve shapes, of which the two first merge fluently, but the third warrants special consideration. These types have been classified by Vogt and Hoffrichter [32] as follows:

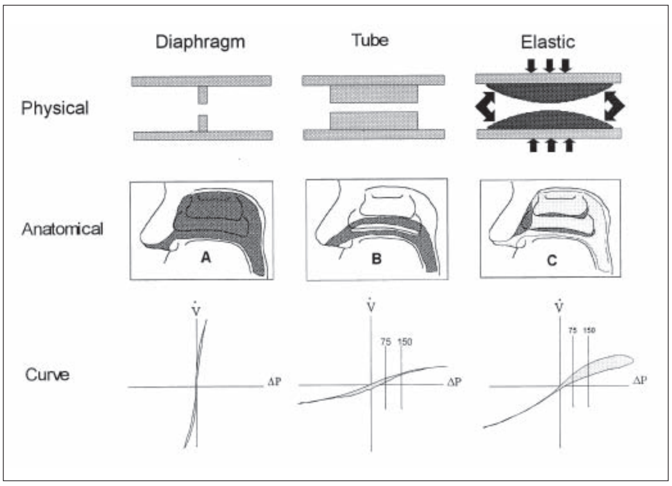


Figure 19. Clinical classification of the results of 4-Phase-Rhinomanometry after Vogt and Hoffrichter [32].

Type A – the diaphragm type

In a decongested state, the nose presents the lowest resistance to the air; i.e. the airflow from the lungs or the surroundings arrives without any major pressure losses and has a certain speed. The narrowing of the flow passage at the nasal entrance – whether from the inspiratory or expiratory direction – causes an acceleration of the airflow as it passes into the enlarged space of the next part of the airway. The unsteady component of respiration has its principle effect in the area of narrowing. Due to the short length l of this narrowness, the unsteady term in equation 6 becomes quite minimal. Consequently, only a slight phase shift between pressure and flow is expected: the curves are closed and virtually go through zero.

Type B – the pipe type

If the nose is swollen, there generates a pipe-like cavity with several parallel connected cavities in the remaining cavity - generally at the lower und middle nasal passage. The air in these pipes is accelerated considerably stronger than at type A, since the flow diameter available is reduced. Therefore, the unsteady term in equation 5 is considerably higher than at type A, so that measurable phase shifts are generated. If the energy supply stops, the accelerated air mass flows on for a short period until its energy is used up by friction. The nose acts as an air pump for a while (Figure 18). A time delay emerges between difference pressure and volume flow rate. This implies a phase shift. As a consequence, the curves are not allowed to go through zero at this point. Due to the pipe system, i. e. at a mucomembraneous-induced mostly blocked nose, the resistance is considerably higher, so that the generating loops, and especially at a very flat curve shape with high resistance values are sparsely bended.

Type C – the elastic type

On the supposition that the classical rhinomanometers do measure qualitatively correct, which should be assumed for most offered rhinomanometers, it should be expected that under the condition of an inflexible nose the displays of the curves in expiration and inspiration are approximately rotationally symmetric. This is not necessarily always the case, because each the increasing and decreasing sides of expiration and inspiration are not congruent. The reason is that the nose is subject to elastically effects, especially at inspiration, which can easily be observed when looking in the nose from below during a powerful inspiration. During inspiration the wing of the nose is contracted and when the flow reduces, the nose opens again *still during inspiration*, because the aspirated wing of the nose returns to its resting position. Similar mechanisms do occur in a considerably smaller extent in the sector of the turbinates or if there are other mobile structures like polyps in the nose.
For the analysis, there now is the problem that the air stream to measure changes its diameter under the influence of the generated flow.
The result is a curve type corresponding to a club whose “hand grip” lies in the expiratory quadrants. This commonly observed result, mainly occurring at modest obstructions of the nose, thus in the clinical most important area of therapy determining diagnostics, has been the reason for numerous errors or misinterpretations up to most recent times. Its definition requires the certain exclusion of cut-off frequency determined construction poverty at the rhinomanometer. But in our judgement the

elastically type is the type at which already the “first view diagnosis” allows essential conclusions on the nose physiology, especially under the aspect of nasal valve surgery and diagnostics of valve dysfunction.
The graphical consideration of rhinomanometrical results in the scope of “first-view- diagnostics” conveys an entirely new impression of the real procedures in the nose to the observer, but above all it immediately reveals in what extend the printed numerical results of the “classical default values” are falsified by the drift apart of the loops.

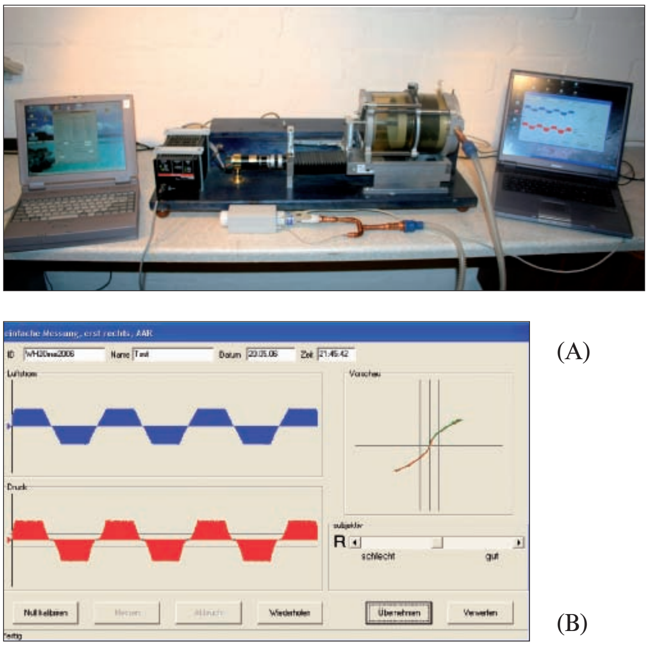
For the practical diagnostics by the help of 4-phase-rhinomanometry, it is important to know that the curve type does not only depend on the geometrical form of the flow channel but above all on the unsteady progresses of the flow. In practice can often be found curves, which as hybrids, cannot be referred to only one single curve type.

5-7 Physical Model of Nose Respiration

Clinical observations and false conclusions from literature studies result in reviewing the mathematical coherence between pressure and air stream. It now became necessary to verify the coherence found in the physical experiment and at the same time to evaluate the influence on the practice of rhinomanometry. For this purpose, different respiratory simulators have been set up (“Artificial Noses”). These consist of a pump, accordant to the lungs, with alternating streamed resistors. A respiratory pump otherwise used in anaesthesiology (Draegerwerke, Luebeck, Germany) had been connected to a stepper motor via a linear gear. This is to be controlled with a special program (Maxon Motor Control) via a PC in a way that trapezoidal respiratory curves will be generated with different respiratory curves, which do thus simulate the conditions of alternate breathing with a quick transition between inspiration and respiration. The rhinomanometric measurements in this model have been carried out by the 4-phase-rhinomanometer HRR 2 (RhinoLab GmbH, Rendsburg, Germany)
The following resistors have been examined at this:

- Diaphragm shaped resistors with a diameter from 3 to 8 mm
- A short pipe with a length of 8 mm and a diameter of 5 m
- A pipe with a length of 60 mm and a diameter of 5 m

Figure 20. Model resistors.



(A)

(B)

Figure 21. (A) Respiratory simulator “ARNO 1” and (B) generated respiratory curves with rhinomanometer HRR 2.

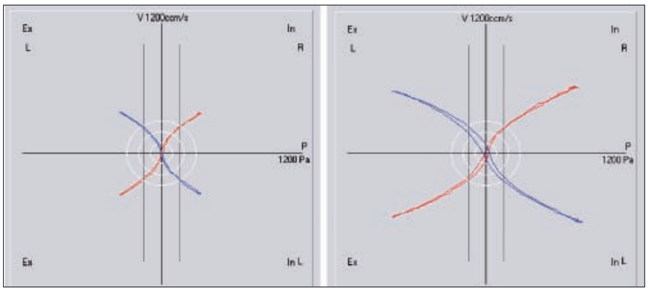


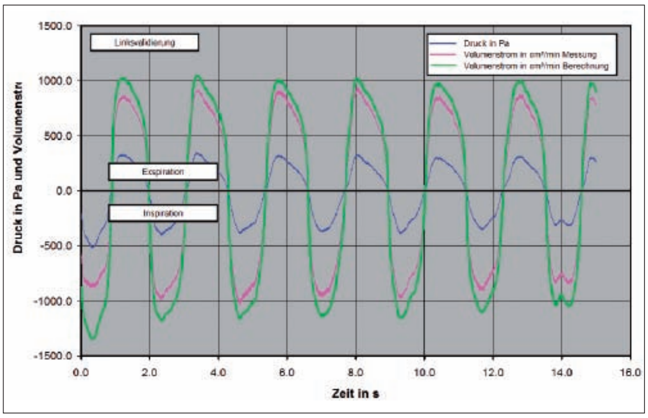
Figure 22. Rhinogram of a diaphragm resistor (quadrant 1 – 3) and of a tubular resistor (quadrant 2-4).

An air stream with a frequency of 12 (quadrant 1 to 3) and 24 (quadrant 2-4) breathes per minute was lead through both resistors. Not any changes occurred at the diaphragm model, when the respiratory frequency increased. At the pipe model a loop demonstrating hysteresis around the zero appeared, which was considerably wider after doubling the respiratory frequency. The remaining flow at a pressure of 0 Pa was measured with 49 and -52 cm^3/s at a respiratory frequency of 12/min and with 62 resp. -62 cm^3/s at a respiratory frequency of 24/min. The opening of the loop then reaches the area of a pressure level of 150 Pa, i.e. the standard measuring point of the ISOANA-standard. With 630 cm^3/s the maximum flow was at the normal range of nose breathing.

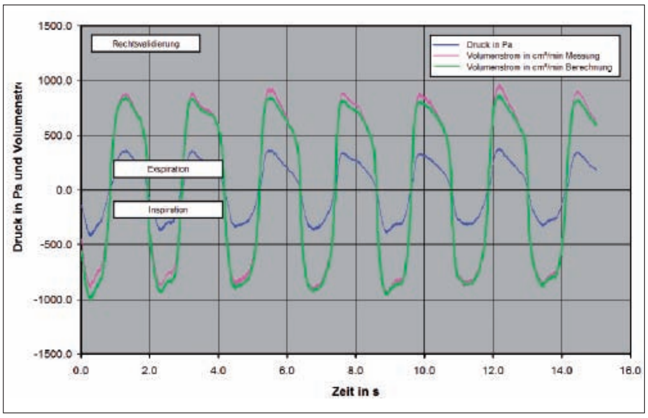
Therewith, the accuracy of the mathematical coherences at the test may be considered confirmed.

A last confirmation of the 4-phase-rhinomanometry as measuring method adapted to the human nose breathing took place recently with the *numerical simulation of the nasal airflow* and the comparison with the measured nose flow [33]. The basic principle is that the numerical information from a high-resolution computer tomogram is used for the construction of a virtual model of the cranium and its cavities. A calculation grid consisting of 3.5 million elements with 1.5 million knots is put in this model. In such a model, the curves for pressure loss and temperature and atmospheric moisture in the nose may be numerically simulated. The nasal airflow of the same test person, measured with the rhinomanometer HRR 2, was used as actual value. At present, the time required for computing is still extensive. As a result, it was shown that the calculated pressure curve and the measured pressure curve only had minor deviations from each other. This proves that the measuring technology as cause of loop generation in the rhinomanometry may be excluded under contemporary technical conditions.

Figure 23. (A-D) Calculated and measured pressure curves in a time-dependent display (above) and in a xy-display (below) for both nose sides (Dr. A.Steinmann, CFX Berlin Software GmbH [35]).

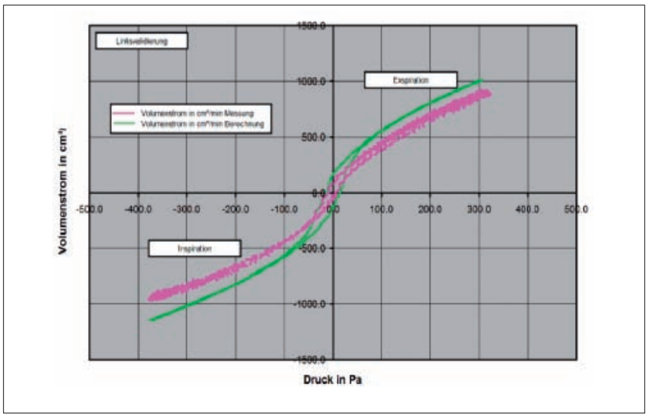


(A)

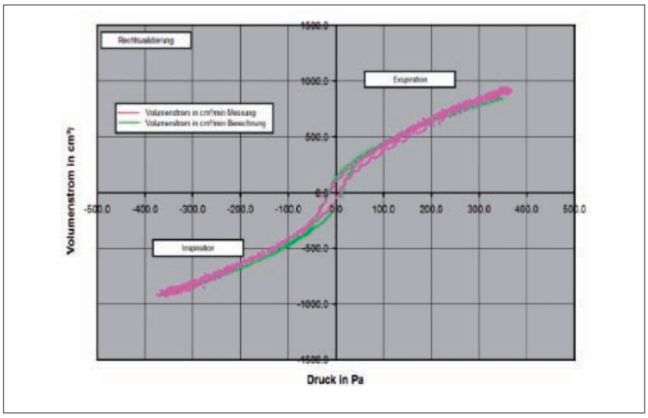


(B)

(C)



(D)



6. New parameters in 4-phase-rhinomanometry, relations between objective findings and the sensation of obstruction. A statistical evaluation of 1580 cases.

Klaus Vogt, Kija Shah-Hosseini, Ralph Mösges, John Pallanch, Wolfgang Hasse

6-1 Introduction

The evaluation of rhinomanometric curves for obtaining clinical information started with the evaluation of strip-chart recordings. An example of this are the time related recordings done by Cottle [12]. Later on, after the introduction of xy-recorders [13,14] it was necessary to investigate which standard points on the rhinomanometric curves would best correspond to the patient´s complaints. The ISOANA committee recommended in 1984 to use the inspiratory flow at a pressure of 150 Pa as a primary measurement point [4]. Should a patient not be able to reach this pressure level, then the pressure level at 75 Pa should be used. These parameters are still the most widely used in rhinomanometry.

6-2 The problems of the present standard evaluation system (ISOANA 1984)

The exponential increase in the data processing power of small computers as well as the development of reliable and affordable sensors in recent years raise the question of whether the choice of optimal parameters should be further considered. Computer programs, which depict loops without expressly using the term "4-phase-rhinomanometry", describe the flow for 150 Pa in phase 1, i.e. the ascending part of inspiration. Some may describe the flow as an averaged value between phase 1 and phase 2.

Rhinomanometric evaluation using these single-point methods has some significant disadvantages:

1. Flow values at a predetermined pressure level describe only one point during the acceleration of breathing. Using computerized rhinomanometry it is possible to use the information of the entire breath, including the effects of airstream acceleration and inertia.
2. It can been shown that there is lower statistical correlation between the flow values at a standard pressure point with data of subjective feeling of obstruction as obtained by a Visual Analogue Scale (VAS).
3. After decongestion 7.34 % of Caucasian subjects with a non-obstructed nose do not reach the level of 150 Pa, and a level of 300 Pa can be reached only by 45.6 % of the subjects. As an example, this means that these patients would have to be excluded from studies using nasal provocation tests. Asian researchers and clinicians report that this number is much higher (see Zhang et al. in chapters 9 and 10!)

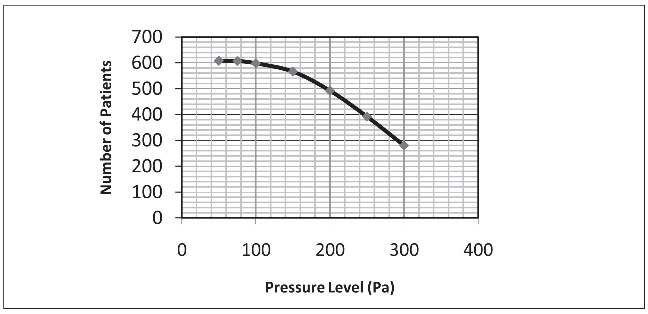


Figure 24. Data loss by increasing pressure level in non-obstructed Caucasian noses (n = 611).

The main argument for a departure from the use of single-point methods of evaluation is the loss of the important diagnostic information, which can be obtained by considering the entire nasal breath.

From the biophysical standpoint as well as from the statistical material, it follows that the "classic" parameters, e.g. flow or resistance at a given pressure level, are less optimal representations of the physical performance of nasal breathing. Except for reflecting the influence of elastic components at the nasal valve, the pressure flow relation as depicted in an xy-diagram does not allow conclusions about the morphological structures of the inner nose. Therefore, the task of rhinomanometry is to give quantitative information of the energetic of the nasal airstream. The resulting question is whether reliable parameters exist, which have a genuine physical basis and that are related to the subjective feeling of nasal obstruction. These parameters should be used as criteria within studies to evaluate the surgical or medical treatment of the nose as well as documenting the influence of environmental factors.

The mathematical and physical considerations above, which have been supported by Computational Fluid Dynamics (CFD) are compelling arguments to accept a loop that is not necessarily running through the intersection point of the x- and y-axis as the true configuration of the rhinomanometric curve. This would imply that equations utilizing the origin of the xy-plot as the starting point of the curve would be only an approximation of the true status of the curve.

In the first publications on computerized rhinomanometry [27,28] the parameters derived from various models of fitting rhinomanometric curves, including the use of polynomial equations were investigated. These models would be suboptimal for describing the looping curves of 4-Phase-Rhinomanometry because they fit to a single curved line, which passes through the origin of the xy-plot. The polar coordinate model of Broms allows results to be obtained at comparable distances from the origin even if a certain pressure limit is not reached, but this method yields parameters that are single values at radius 2 or 3 or that represent the amount of curvilinearity but do not give a representation of the information in the entire breath. The many models that had been proposed, including the polynomial curve fitting, Brom's Polar coordinate fitting and many others all yield one or more numbers. In choosing which numbers to use from these models, investigators may be emphasizing only certain parts of the pressure-flow curve. The resistometry method used by Mlynski [19] calculates a parameter, the hydraulic diameter of the nose, at the point of the lowest flow, where the air stream is changing from inspiration to expiration, which is the region of the highest probability of errors. Using 4 breathing phases, it is necessary to discuss 4 separate and distinct values to describe the entire breath.

In any method of describing the data obtained by objective measurement of the nasal airway, the key would be to find the parameter or parameters that can be derived from the pressure-flow data and show the best correlation with the patient's symptoms. The most clinically relevant model would be the one that, when compared by statistical analysis with the parameters from all of the other models, shows the best correlation with the patient's symptoms of nasal airway obstruction. A clinical evaluation of the statistical correlation with symptoms in 4-phase-rhinomanometry had not previously been done.

The following parameters have been modified or introduced by us into the practice of rhinomanometry to allow the reflection of the special condition of the analysis of 4 different breathing phases:

1. Vertex Resistance
2. Effective Resistance

6-3 Vertex Resistance

Vertex Resistance VR is the resistance (differential pressure divided by flow) of the nasal airstream at the point of maximum flow during inspiration (VRin) or expiration (VRex) in a breath of normal length or depth. We have chosen "Vertex Resistance" as a new term instead of "Peak Flow Resistance" because this term is widely used in pulmonology for the resistance of breathing during maximal inspiration and expiration. It is distinctly different from the PNIF (Peak Nasal Inspiratory Flow) for the evaluation of the nasal airstream as recently discussed by Bermüller et al. [36]. It corresponds to the method of reporting resistance at maximum pressure and flow used by Cottle [12], and then by McCaffrey and Kern [28], Sipilä [37], Naito [38], and Pallanch [27].

The advantage of Vertex Resistance is that it is measured within the steady phase of the nasal airstream, where acceleration is not occurring. As Cole [39] already pointed out, this is the longest part of the breathing cycle. This is when the pressure- and flow-curves run parallel to each other reflecting a linear relationship. It follows that the calculation of resistance as a linear quotient in this region is physically and mathematically correct. It can be measured during inspiration and expiration, but does not represent the total breath.

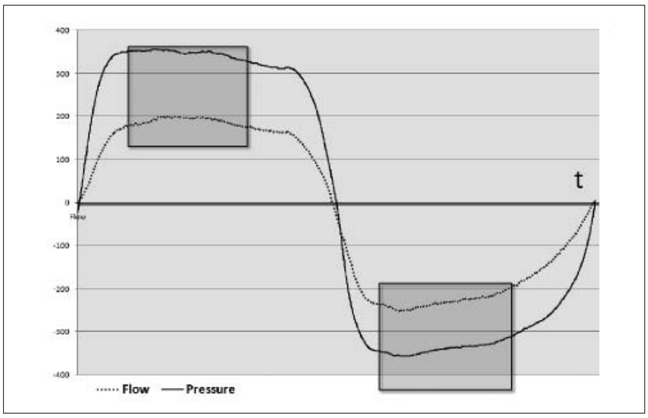


Figure 25. Vertex Resistance. Within the marked regions, the relationship between pressure and flow is approximately linear and changes remarkably less than in the region of acceleration or deceleration of the nasal air flow that occurs before and after the transition from inspiration to expiration.

6-4 Effective Resistance

The term "Effective Resistance (Reff)" was introduced into clinical rhinomanometry by Vogt and Hoffrichter [32] in 1993. "Effective" values are calculated in electrical engineering using the equations for calculating energy in alternating current. An effective value is the integral of measured values over the time interval of interest:

$$W_{eff} = \sqrt{\frac{1}{T}\int_0^T w^2 dt}$$

In this equation W can be either the differential pressure Δp or the Flow $\dot{V}$. By dividing these effective values by each other the Effective Resistance is obtained:

$$R_{eff} = \frac{\Delta P_{eff}}{\dot{V}_{eff}} \left[Pas / ccm \right]$$

Example: In 4-Phase-rhinomanometry every averaged breath contains 2000 measurements of flow and differential pressure. These values are summed up and divided by each other. The calculation of Effective Resistance can be carried out for the inspiratory part of the breathing cycle as well as for the expiratory part and the total breath.

By the integration of the measurement values over the time interval, the element of time, which one needs for getting the necessary air into the lungs, is included as an essential diagnostic factor. It is not only important for the feeling of impaired nasal breathing, that the nasal resistance is not outside a comfortable level but also that the time for a breath lies within a bearable range.

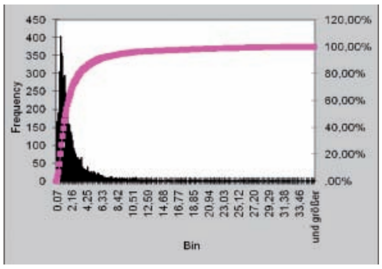
6-5 The Effective Resistance evaluates the work of nasal breathing and has a significant relationship with the subjective sensation of obstruction

Before introducing a new parameter into the international conventions ("standards") for rhinomanometry, we investigated the statistical distribution of the parameter. This also enables a classification of the airway testing results in terms of severity of obstruction compared to the rest of the population tested. The first publication of the statistical distribution of Effective Resistance and Vertex Resistance values was presented at the Congress of the European Rhinologic Society in Ulm 2002 by Vogt et al. [40]. They evaluated data from more than 5000 rhinomanometric tests, obtained from several institutes and clinics and performed with the same technique. The non-classified data covered the total range of obstruction. They showed that the distribution of Reff and VR was dramatically skewed to the left, but achieved a normal distribution after logarithmic transformation. Furthermore, the investigators performed statistical evaluation of the pooled data to ascertain whether there was a significant correlation with subjective values obtained by VAS. They found that Reff and VR had a significant correlation with symptoms but that other rhinomanometry testing parameters, including flow at 75 and 150 Pa, did not. Having a normal distribution allows the use of parametric statistical methods. Interestingly, the statistical testing after logarithmic transformation of the airway data yielded an even stronger correlation with symptoms. Similar results were obtained in another study by Shiraz [41].

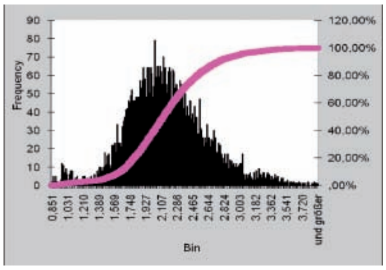
The logarithmic transformation has some precedent in physiology, if we refer to the law of Weber-Fechner (1860). Ernst Heinrich Weber in 1834 has defined the "just noticeable difference", or threshold, for the intensity of a stimulus. Gustav Theodor Fechner found in 1860, that the sensation of a stimulus increases linearly as the stimulus increases logarithmically. That is the basis for the dB-scale in acoustics and is also valid for the sensation of the effort, which is necessary for the act of breathing. The "Logarithmic Pressure Level" was already introduced into rhinology by Mlynski [19]. The stronger correlation between resistance and subjective data after logarithmic transformation is consistent with these well-known laws of neurophysiology.

To verify the above results, the following material has been statistically investigated:

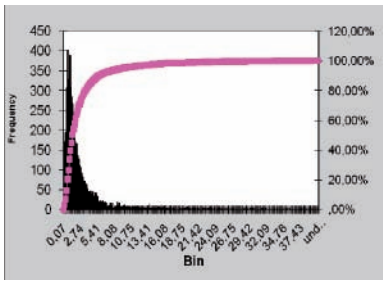
Figure 26. Histograms of the data analysis of Vertex Resistance and Effective Resistance by Vogt et al. [40] before and after logarithmic transformation. N= 5292.



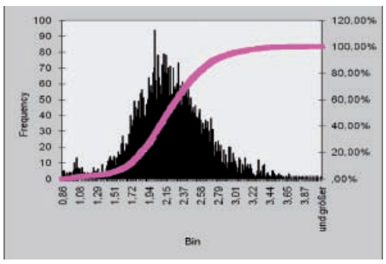
(A) Effective Resistance, without decongestion.



(B) Log(100 Reff), without decongestion.



(C) Vertex Resistance, inspiratory, without decongestion.



(D) log(100VR), inspiratory, without decongestion.

6-5-1 Material and rhinomanometric method

The material for this investigation was collected from more than 2000 patients, who visited the clinic of K.Vogt (Praxis und Tagesklinik, Prof. Dr. Dr. Klaus Vogt, Rendsburg, Germany) between 2005 and 2008 because of rhinological problems. All investigations have been carried out by 3 experienced assistants using the 4-phase Rhinomanometer HRR 2 (RhinoLab, Germany). Most of the investigations have been carried out as decongestion tests, i.e. 2 subsequent measurements, where the second measurement has been done 10 min after instillation of 1% solution of xylometazoline as spray. From the data sets, those with missing subjective evaluation by a VAS-scale have been excluded.

All data sets have the same length of 2000 for the "representative breath". The program generates automatically a table, which contains the deviation of the curve around zero, the one-point values for all 4 phases at 50, 75, 100, 150, 200, 250 and 300 Pa, the maximum flow, maximum pressure, the pressure at maximum flow, the Effective Resistance for inspiration, expiration and the total breath and the values obtained on a VAS with a range from 0-100 as subjective parameters. By transferring these values into SPSS or MS Excel, the parameters as discussed below have been calculated.

The following abbreviations for parameters have been applied:

VR	Vertex Resistance
VRin	Vertex Resistance at inspiration
VRex	Vertex Resistance at expiration
LVR	Logarithmic Vertex Resistance, LVR = log (10 VR)
LVRin	Logarithmic Vertex Resistance at inspiration, LVRin = log (10VRin)
LVRex	Logarithmic Vertex Resistance at expiration, LVRex = log (10VRex)
REFF	Effective Resistance
REFFin	Effective Resistance at inspiration
REFFex	Effective Resistance at expiration
REFFtot	Effective Resistance for the total breath
LER	Logarithmic Effective Resistance, LER= log (10REFF)
LERin	Logarithmic Effective Resistance at inspiration, LERin=log (10REFin)
LERex	Logarithmic Effective Resistance at expiration, LERex=log (10REFex)
LERtot	Logarithmic Effective Resistance for the total breath, LERtot=log (10LREFtot)

In contrast to our previous investigations we used the logarithmic data transformation after multiplying the measured value by 10, to get a practicable scale for the grading of obstruction and to avoid negative numbers for measured resistance values less than 1.

6-6 Statistical methods

First, correlations (on the level of 0.01 (two-sided) significance) between VAS (subjective sensation) and all measured values VRin, VRex, REFFin, REFFex and REFF were calculated according to Pearson. In addition, the logarithmic values of these variables were correlated with VAS (subjective sensation; Table 3).

Table 3. Correlation between VAS and Resistance Values.

		VAS (subjective sensation)
LVRin	Correlation (Pearson)	-0.508
	significance (two-sided)	0.000
	N	1353
LVRex	Correlation (Pearson)	-0.497
	significance (two-sided)	0.000
	N	1353
LVRin	Correlation (Pearson)	-0.514
	significance (two-sided)	0.000
	N	1353
LVRex	Correlation (Pearson)	-0.497
	significance (two-sided)	0.000
	N	1353
LER	Correlation (Pearson)	-0.519
	significance (two-sided)	0.000
	N	1353
VRin	Correlation (Pearson)	-0.364
	significance (two-sided)	0.000
	N	1353
VRex	Correlation (Pearson)	-0.300
	significance (two-sided)	0.000
	N	1353
REFFin	Correlation (Pearson)	-0.352
	significance (two-sided)	0.000
	N	1353
REFFex	Correlation (Pearson)	-0.343
	significance (two-sided)	0.000
	N	1353
REFF	Correlation (Pearson)	-0.362
	significance (two-sided)	0.000
	N	1353

The correlations of the logarithmic values were higher, when based on the Weber-Fechner law. The values were used for creating five classes, wherein subjective sensation was classified in 20 % percentiles, resulting in values for LVRin and LVRex in the appropriate five classes.

Table 4. Classification of VAS classes according log 100 *resistance Values.

Classes		LVRin	LVRex
1	N	284	284
	Mean	2.42	2.43
	Standard deviation	0.36	0.36
2	N	277	277
	Mean	2.20	2.22
	Standard deviation	0.34	0.33
3	N	257	257
	Mean	2.04	2.07
	Standard deviation	0.30	0.27
4	N	281	281
	Mean	1.91	1.96
	Standard deviation	0.29	0.26
5	N	254	254
	Mean	1.86	1.91
	Standard deviation	0.33	0.294

In addition, LVRin, LVRex, LERin, LERex and LER were classified in 20 % percentiles. The results are the values for five classes of VAS (subjective sensation).

Table 5. Classification of subjective sensation.

Classes						
		LVRin	LVRex	LERin	LERex	LER
1	N	260	268	261	265	262
	Mean	64.33	64.26	64.58	64.15	64.73
	Standard deviation	23.48	24.01	23.12	23.81	23.58
2	N	262	256	261	262	262
	Mean	56.88	55.61	56.98	56.08	56.11
	Standard deviation	24.69	24.82	24.82	24.99	24.58
3	N	269	264	271	259	267
	Mean	47.48	49.23	47.72	49.15	49.67
	Standard deviation	25.59	25.92	25.32	26.20	25.87
4	N	269	275	264	278	270
	Mean	35.51	34.46	34.79	34.48	34.20
	Standard deviation	25.63	24.23	25.24	24.00	23.93
5	N	293	290	296	289	292
	Mean	21.79	22.07	21.92	21.88	21.16
	Standard deviation	22.61	23.22	23.00	22.98	22.57

The areas of classification are depicted in Table 6.

The histograms in Figure 27, as examples, show that the distribution of the values corresponds with the diagrams of Vogt et al. [40] as shown in figure 26.

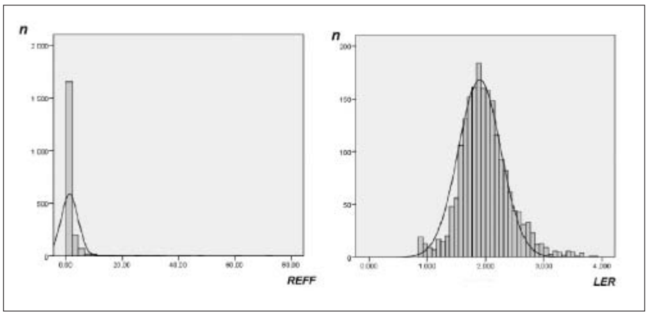


Figure 27. Statistical distribution of Effective Resistance REFF and Logarithmic Effective Resistance LER within 1580 non-classified cases without decongestion.

6-7 Clinical classifications of LVR and LEFF

The statistics above are a part of comprehensive calculations including also the “classic” rhinomanometric parameters. They have been carried out by using the logarithm of the value multiplied by 10. However, to set up a proposal for a standardized clinical grading of obstruction or conductance of the nose, it is more convenient to use the logarithm of the value multiplied by 100 with equal differences between the classes. These values are valid for Caucasian noses before any decongestion by drugs or by body exercise in normal room temperature as shown in Table 7.

Table 7. Clinical classification of obstruction and conductance of the nose by Logarithmic Vertex resistance LVR and Loga-rithmic Effective Resistance (log10R).

	Log10R (VR, REFF)	Obstruction, Resistance	Conductance
1	<= 0.75	very low	very high
2	0.75 - 1.00	low	high
3	1.00 - 1.25	moderate	moderate
4	1.25 - 1.50	high	low
5	> 1.50	very high	very low

Table 6. Resistances (log 100*R) in classified VAS-values.

class	LVRin	LVRex	LERin	LERex	LER
1	<= 1.749	<= 1.814	<= 1.728	<= 1.770	<= 1.757
2	1.750 - 1.970	1.815 - 2.000	1.729 - 1.954	1.771 - 1.956	1.758 - 1.961
3	1.971 - 2.152	2.001 - 2.170	1.955 - 2.137	1.957 - 2.129	1.962 - 2.136
4	2.153 - 2.377	2.171 - 2.386	2.138 - 2.378	2.130 - 2.348	2.137 - 2.365
5	2.378+	2.387+	2.379+	2.349+	2.366+

The classes differ significantly from one another according to Wilcoxon (<0.001). LER is used for the final classification based on the highest correlation (-0.519).

6-8 The correlation between subjective and objective parameters

The results of rhinomanometry do correlate with the symptom of nasal obstruction. Some have denied this. As recently as 2005 it was stated *"Surgeons are reluctant to use objective measurements …as there is general agreement that objective measurements do not correlate with the patient's symptoms of nasal obstruction"* [(42)].

We sincerely hope that there is no "general agreement" about this, since only critical reviewing reveals significant evidence to contradict the statement that the results of airway testing by rhinomanomety do not correlate with symptoms. A better correlation after logarithmic transformation of the important parameters will contribute to a change in opinions.
Several clear-cut correlations do exist. First, a correlation has been shown between the side of greatest symptoms of obstruction and the side of greatest resistance in symptomatic patients [(27,37)]. Second, there is a correlation between the degree of symptoms (mild, moderate, severe) and the magnitude of resistance in symptomatic patients [(27, 38, 44-47)].
We acknowledge that some studies have reported that no correlation between the degree of obstruction and the magnitude of resistance was found in symptomatic patients [(48-50)], but we note that the preponderance of evidence is otherwise, particularly if appraised in the light of the points to consider in the discussion that follows.

It is important to watch for several elements when reviewing the results reported in these studies:

1. Were the symptoms assessed at the time of the testing? The nasal cycle introduces some variability in unilateral measurements that could change the correlation with symptoms if the two are not recorded at the same time.
2. How was the reported result obtained? Resistance values vary at different parts of the curve. It has also been shown that certain parameters have a stronger correlation with symptoms than others [(27, 40, 41)].
3. Did the patients have any symptoms of nasal obstruction? It is easier to find a correlation between objective airway results and symptoms in patients who have symptoms. The lower resistance values for normal subjects may not have a sufficient difference from baseline (or "threshold") resistance to show significance compared to noise in the data. To compound the effect of noise, it has been noted that there is a variation in "resting nasal resistance" [(51)].

It is not surprising that only a weaker correlation with degree of symptoms has been demonstrated in some of the studies of patients who did not have symptoms [(52,53)]. This should not pose a problem in the clinical evaluation of patients who have a symptom of nasal obstruction. It has been shown that it is easier to demonstrate the correlation between objective airway results and symptoms for each side of the nose than for the total nasal airway [(38, 42, 46, 48, 55)].

In comparing groups of patients who have symptoms with normal subjects, the mean unilateral resistance of the nasal airway of normal subjects was significantly less than the mean resistance of the worst side in patients with unilateral obstruction but was not significantly different than the mean resistance of the non-obstructed side in patients with unilateral obstruction. This further supports a correlation between measured airway restriction and the presence of the symptom of nasal obstruction. Furthermore, the total resistance for patients with moderate and severe bilateral symptoms was greater than the total resistance for normal subjects and the total resistance for patients with moderate and severe unilateral symptoms was greater than the total resistance for normal subjects [(56,57)].

Another thing to keep in mind in the analysis of the correlation between objective results and symptoms, is that for the sensation of comfortable breathing, there are a range of thresholds at which patients become aware of the sensation of obstruction. Because the range of resistance values for patients without symptoms has an area of overlap with a population that has obstructive symptoms, it is possible for individual resistance values measured in this range to be the same for some patients who complain of obstruction as for some who do not. It follows that there is a range of thresholds at which different patients will feel nasal obstruction. The existence of a range of threshold resistances could explain why comparisons between groups (e.g. normal patients vs. patients who feel obstruction) may sometimes need moderate or severe levels of symptoms or resistance to demonstrate a difference or a correlation (particularly if the data in the study is noisy). The phenomenon that there is a range of values rather than a single airway resistance at which different patients become symptomatic (58) also explains why it is not always possible to identify individuals who will feel obstructed solely on the basis of airway data. Despite this, there is enough of a correlation that a single threshold value has been used successfully by many authors have used a single threshold values for normal versus abnormal airway measurements [(39,57,59-61)].

Another way that the correlation between objective results of airway testing and symptoms has been demonstrated is in showing the correlation between changes in symptoms that correspond with changes in airway testing results. Even if there is sometimes not a correlation evident between initial baseline mild symptoms and mild resistance values, a significant correlation can be found between the changes that occur in symptoms and resistance after medical or surgical therapy. Cole and Roithmann thought that changes in airway dimension were as useful as absolute values in many investigations [(62)].

An often-demonstrated example of the correlation between changes in symptoms and changes in resistance is the correlation in symptomatic patients, between improvement in symptoms and improvement in resistance after surgical intervention (60,63-66). Furthermore, a correlation has been shown between changes in resistance and changes in symptoms after decongestion of the nose (53,67).

Once we accept that this evidence establishes that objective testing results do correlate with symptoms, the results of testing are credible even in the intermittent cases when the results of testing do not match the symptoms. It is when there is a mismatch between the objective testing result and the symptoms or exam findings that the test may be most helpful, by leading to the discovery of the cause of the discrepancy. Also, knowing that there is a correlation allows us to understand the importance and utility of the airway information. We want to know how to best help our patients. The probability of success of treatment directed at increasing the size of the airway is higher for treating symptoms that are due to airway restriction than for treating symptoms that are due to causes other than airway restriction e.g. psychogenic, sinusitis, COPD. Testing can confirm the presence of airway restriction. Airway testing can also help us to determine which part(s) of the airway are contributing to the restriction. The importance of knowing this is that the probability of success of treatment directed at increasing the size of the airway is higher when the pathology that is modified is the pathology contributing to the symptoms.

We have shown that in patients with “non-diseased” mucosa who complain of nasal obstruction, a correlation has been shown between the sensation of nasal obstruction and the results of objective testing of the airway. Understanding the qualifications regarding the studies that were pointed out above, we can use the enhanced correlation between symptoms and 4-phase-rhinomanometry to: refine our diagnosis, refine our treatment plan, better counsel our patients about treatment options, and objectively assess the results of the treatment that we provide.

The here reported statistical results about the much higher correlation between the logarithmic Vertex Resistance and Effective Resistance and the subjective feeling of obstruction are related to well known physiological basics. Therefore, the introduction of these parameters into the clinic is mandatory to improve the evidence of rhinomanometry as a clinically important method. It must be the practical step that has to follow the intensive multidisciplinary work as described in the chapters before.

7. Nasal valve diagnostic by 4-phase-rhinomanometry

Klaus Vogt

7-1 Introduction

The previous chapters dealt with reproducible phenomena of the air stream through a more or less rigid cavity. However, for a diagnostic investigation of the nasal valve, one has to consider a movable compartment at the nasal entrance that changes the shape of its anatomical structure under the influence of the nasal airstream. A problem evident from the technical point of view is that the investigated structure changes its shape and aerodynamic behavior under the influence of the measurement process itself.

Review of the numerous publications about the "nasal valve" brings one to the conclusion that the term "valve" is not always correctly used. Therefore, it is worth to define exactly the topic of our interest.

In a technical sense, a valve is a device for the control of an air or liquid stream. It can be a device to open, close or regulate fluid flow, and it can opened or closed under predetermined pressure conditions. Depending on the outflow path, it can redirect a flow in only one direction or in different directions. Every valve is movable by definition. Thus, we have to discriminate between the term "stenosis", an immobile narrowing of the nasal airway, and the temporary partial or total closure of the nasal entrance by a functional valve. In addition, a combination of functional valve problems and a fixed stenosis is possible.

The nasal valve is not a static anatomical structure but rather a dynamic functional structure. It consists of several anatomical components, which can be closed by a forced inspiratory airflow to suck off mucous from mucosa and paranasal sinuses. Another function may be the limitation of the volume of unconditioned air, which can be inspired with a single breath, comparable to a "shock-absorber". The nasal valve can be opened to a small extent by forced expiration and can be completely closed by forced inspiration.

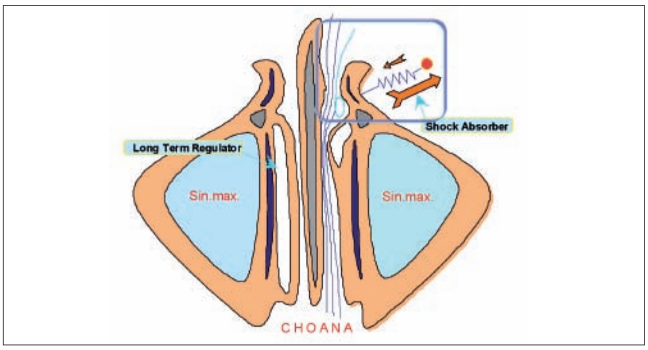


Figure 28. The spring mechanism of the nasal valve is directed outwards more than inwards.

The prerequisite for the onset of the closing of the nasal valve is the so-called Bernouilli´s effect. The act of sniffing utilizes this effect. The greater differential pressure under a wing generated by an airstream is necessary for sailing and airplane flight. By "sniffing" we produce by this effect the increased turbulence, which transports molecules for smelling into the superior nasal channel along the olfactory epithelium. This physiological valve manifestation of the Bernouilli-Effect is symmetrical and can be released at any time by decreased acceleration of the nasal airflow. Active widening of the nasal entrance by the action of adjacent muscles can have the opposite effect. Under pathological anatomical conditions, additional Bernouilli-effects may occur. Other examples are a narrower inferior nasal passage working as a nozzle and producing a jetstream, or a septal spur causing turbulence. A prominent upper lateral cartilage or prominent medial crus of the alar cartilage also can be responsible for an irregular air stream. Another cause for the premature onset of valve closure may be weakness of the cartilages or the components of the skin forming the nasal entrance. In this case, the surgical approach is completely different. Valve dysfunction because of weakness is mostly found symmetrically.

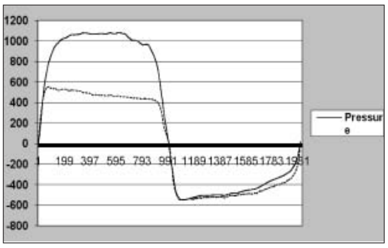
7-2 Diagnosis of nasal valve problems by 4-phase-rhinomanometry

Graphs of valve action in 4-phase-rhinomanometry always show an asymmetrical pattern with a wide open loop at the inspiratory side and a less prominent loop in the expiratory side similar to a bent baseball bat (Type C in the classification of Vogt, Figure 19). At the beginning of the breath (phase 1), the nasal channel maintains its shape. When the flow reaches maximum levels, collapse and narrowing of the channel can occur, and at the same differential pressure, less airflow passes through the nose (phase 2). When the inspiratory airflow decreases, the valve opens again and returns to its resting position by the end of the inspiratory part of the breath. Expiration may slightly expand the nasal wings (phase 3), which then return to the starting position in phase 4. The intersection of such curves shifts frequently toward the expiratory side because the nose in those cases works like the "wind-bag" of an organ.

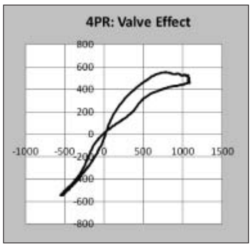
The onset of nasal valve action cannot be reflected exactly in rhinomanometric recordings, because the degree of the collapse seen in the initial recording depends on the acceleration of the flow, not just on the amount of flow. To best test this, patients should be taught, to "sniff" quickly during the initial recording (see also 8-7-3 on p.38 !). By doing this, a "first-glimpse-diagnosis" is obtained. If there is suggestion of a valve problem, this can be confirmed by different additional tests as described below in this chapter. Such testing is very effective in noses with weak soft tissue or cartilage structures (Figure 28). For successful testing of the valve, the examination technique has to provide free motility of the structures at the nasal entrance. Therefore, the application of preformed plugs for the attachment of the pressure hose invalidates the test and any information about the nasal valve is lost (see chapter 8)

Numerical parameters can suggest the presence of valve collapse when a notable difference is seen between Effective Resistance (Reff) and Vertex Resistance (VR). While VR is measured at the point of highest flow at the uppermost part of phase 1, Reff is calculated from the entire breath and includes the notably higher resistance in phase 2, when the nasal entrance is narrowed under the influence of the airstream.

Figure 29. (A, B) Expressed valve effect in xt- and xy-recording. Analyzing the xt-graph, it is clearly evident that during the acceleration phase, the flow-line follows the pressure line up to a level of 700 Pa or 550 ccm/s. At this point, the pressure continues to increase but the flow decreases. At the end of expiration, there are only smaller differences in deceleration of the air stream.

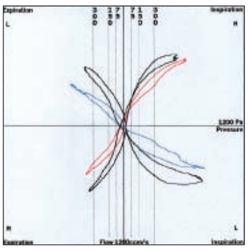


(A)



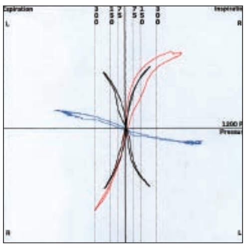
(B)

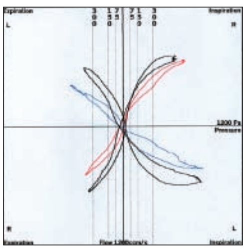
Figure 30. (A-C) Different valve phenomena (Decongestion Tests). (A) Valve problems caused by weak structures at the nasal entrance on both sides with the left side of greater magnitude than the right side. (B) Clearly expressed valve phenomenon before the decongestion test on the right side. After decongestion, the valve effect is no longer visible because of less accelerated breathing. (C) Septal deformation: Normal right side, left side remarkable valve phenomenon.



(A)

(B)

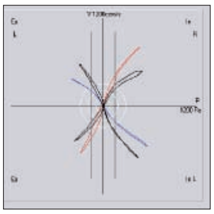


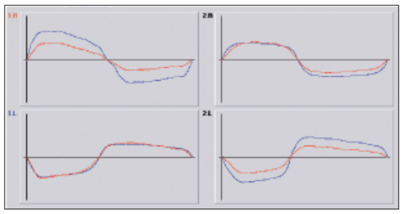


(C)

Figures 31 and 32 show an extreme case demonstrating the effect of modified breathing (“sniffing”) during the rhinomanometric measurement process: the patient was suffering from a medium grade obstruction but reported severe difficulties in nasal breathing during sports. A “normal” rhinomanometry showed the pattern as in Fig. 31 A and B.

Figure 31. (A) Non-activated valve. (B) x/t –graph of the same case.

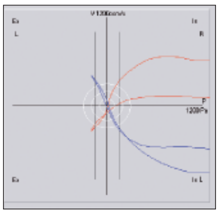


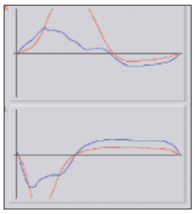


(A) (B)

After breathing in “sniffing mode” (see chapter 8!), a nearly total collapse of the nasal wings occurred and the rhinomanometric pattern was changed as seen in Figure 32.

Figure 32. The “capacity effect” is visible as well in the xy- as in the xt-graphs. In this case, the differences between LREFF and LVR are extremely high because the Vertex Resistance is not affected by the nasal valve, furthermore the differences between the inspiratory and expiratory values are very high because of the missing effect of the nasal valve in expiration.





(A) (B)

Figure 33. Spreader Device Airmax®. Different types for sporters (blue) and snorers (orange).

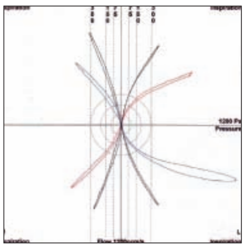


Figure 34. 4PR-rhinogram with moderate valve phenomenon left side. Dramatic improvement is seen after insertion of a spreader device (“Airmax”).

Table 8 shows clearly that valve effects can also be evaluated numerically by 4-phase-rhinomanometry.

Table 8. Changes of the resistances after activation of the valve.

	LVRin	LVRex	LREFFin	LREFFex	LREFFtotal
Right side	1.07	0.77	1.41	0.76	1.36
Left side	1.13	0.67	1.20	0.66	1.11

7-3 Additional tests of clinical valve phenomena

To identify the causes of the identified valve phenomena, first an endoscopic inspection should be performed, especially when there are unilateral findings.

One method to obtain more information about the role of the nasal valve is to use a spreader-test. These tests can be carried out to predict the efficacy of commercial spreader devices that are worn by some sportsmen or snorers. The success of these devices is obtained by different mechanisms: in sports with dramatically elevated airflow through the nose, spreaders can prohibit the physiological consequence of the Bernouilli-effect by preventing the flow induced alar collapse [68]. The role of the nasal valve is not sufficiently investigated up to now, but spreader devices like the plastic adhesive strips Breath-Right® (3M, USA) or plastic devices that insert into the nostrils as Nozovent® (Optima, Moosburg, Germany and different other markets), Nasanita® (Siemens and Co., Bad Ems, Germany) or AirMax® (Airmax Cie., Oegstgeest, The Netherlands; Figure 34) and others are reported to work reliably in many cases. Because of the low nasal flow rate during sleep, the second requirement for eliciting the Bernouilli-effect is missing. Hence, the mechanism by which improved airway function can be achieved is by widening the elastic structures at the nasal entrance. 4PR-tests after insertion of spreader devices can predict the success of functional surgery of the nasal valve (Figure 35).

The effect of the face muscles can be tested by 4PR-controlled tape-traction-tests, which are also proven tests to demonstrate the functional improvement obtained by correction of a drooping nasal tip (Figure 33).

Figure 35. Tape-Traction-Tests for the evaluation of valve phenomena. (A) Skin Retraction Test (B) Tip Suspension Test.

(A) (B)

In summary, analyzing the 4 phases of the human breath in Rhinomanometry yields important information about the intra-individual behavior of the nasal valve. The semi-quantitative diagnosis can predict the success of surgery or of spreader devices in the anterior part of the nose.

8. Practical aspects of 4-Phase-Rhinomanometry

Klaus Vogt, Alfredo A. Jalowayski, John Pallanch, Kaspars Peksis, Pavel Zaporoshenko, Luo Zhang

8-1 Introduction

4-Phase-Rhinomanometry, founded on strong theoretical background and technical advances, can fully expand the information that can be obtained from the nasal air stream and therefore improve the diagnostic capabilities of "classic" rhinomanometry. However, to achieve the best results, it is necessary to carry out the investigation procedures carefully and to follow the recommendations given by the ISOANA, which were reaffirmed during the Consensus Conference in Brussels in 2003. The following remarks refer to those recommendations as updated in the "Consensus report on acoustic rhinometry and rhinomanometry" [30]. In the addendum to this report practical advice is given based on the experience of the authors of this chapter.

8-1 4-PR data acquisition and recording techniques

The methods of data acquisition for flow and differential pressure should provide linearity in a range of ± 1200 ccm/s for the flow measurement and ± 1200 Pa for the pressure measurement. The linear behavior of the data acquisition channels should be documented by the manufacturer. The response time of both channels should provide a reliable measurement of flow and pressure variations of > 80 Hz. The error due to the apparatus should not exceed 2% FSO (Full Signal Output). The range of 1200 ccm/s or Pa doubles the range of the classic rhinomanometry standard because for the provocation of valve effects higher flow rates and acceleration are necessary.
The standard graph should be as in Figure 36.

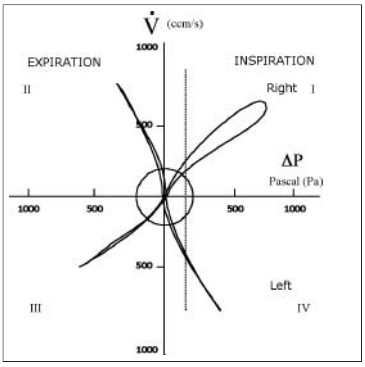


Figure 36. Standard Graph for 4-Phase-Rhinomanometry.

8-2 Hygienic Requirements

"Any part of the system, which can be contaminated either by contact or by the exhaled air, must be easily sterilized according to general hygienic prescriptions or exchangeable by disposable parts."

This trivial sentence from the ISOANA recommendations was obviously not considered as being important in old rhinomanometry models. Worldwide, producers of new equipment have to pay attention to this issue. General requirements of quality standards for medical products must be followed, as recommended by ISO or other international or regional normative regulations.
A particular problem of cleaning is the pneumotachographs and mass flow meters, because of their sensitivity to fluids or heat. The best way to exercise hygienic safety is with the use of bacterial filters, or disposable filter patches, which are widely used in anesthesiology and in emergency medicine. The use of disposable masks or pneumotachographs is a more expensive solution, while tubings made from silicone are sterilizable.

8-3 Calibration

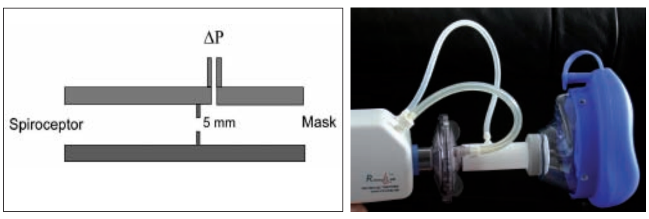
8-3-1 Basic calibration

The basic calibration of new equipment must be carried out by the manufacturer. The calibration date should be documented. The maximal time between re-calibrations should be recommended by the manufacturer; however, it should not exceed 2 years. The pressure channels on all instruments must be calibrated in the factory with an accurate water or red oil manometer, and the instrument should allow manometric rechecking of the calibration by the user. Instruments that record flow must be calibrated with accurate flow meters in the factory and specified by voltage output per unit flow.

8-3-2 Verification of calibration

A standard resistor for the verification of the calibration by the user must be a part of the equipment. The flow values of this resistor should be recorded between 100 and 300 ccm/s during a differential pressure of 150 Pa. The rhinomanometric curve of this device should be documented as a data file as well as printed with the seal of the manufacturer. The data file should be stored by the manufacturer as well as by the user. The design of the control resistor should correspond to the drawing in Figure 37.

Figure 37. Calibration Control Device (Example). A schematic, B within HRR3-system (RhinoLab, Rendsburg, Germany)



A B

Table 9. Calibration of rhinomanometric devices.

	Definition	Responsibility
Calibration	First calibration of the system	Producer
Control of Calibration	Control by preformed resistors (part of system)	User
Re-Calibration	Re-calibration of the system depending on results of calibration control or in recommended time intervals.	Producer, authorized personnel
Offset-Control	Control of zero before starting a measurement (software)	User

8-3-3 Readjustment of calibration

The hardware and/or software must allow readjustment of the calibration (Table 9), which should be done by authorized personnel, if repeated measurement results deviate from the first calibration by > 5%.

The worldwide comparability of clinical and research results depends on reliable calibration methods. For a limited time of 2-5 years the worldwide used static calibration should be further applied, but the user should be obliged to control his instrument by a standard resistor. If a rhinomanometric investigation gets a medico-legal impact, as in studies for authorities approving drugs effective in the nose, in a lawsuit, or for the quantitative assessment of obstructed nasal breathing for insurance law purposes, then proof must be provided showing that calibration has been done properly.

Research on the influence of the dynamics of the nasal airflow on the measurement results and the development of dynamic calibration methods is in progress in different fluid dynamics research institutes.
It is important that when rhinomanometers are used based on the flow measurement by mass flow meters, that the rhinomanometer has to be adjusted to the elevation above sea level, because the air mass depends on the elevation. Generally, this adjustment is implemented in the software of the device. In studies done at high elevation, the results can also be corrected numerically later on.
Depending on the rhinomanometer – it may be necessary to make a reset of the zero-line before the measurement process. The reset starts in some rhinomanometers automatically, in others by pressing a “button” or by a mouse click.

8-4 Masks and connection tubings

In addition to the electronic hardware, the type of masks and connection tubings used are also important for reliable rhinomanometric measurements.

8-4-1 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 tube can be excluded….” (consensus report [30]). 2 different types of masks are generally applied (Figure 38):

- Anesthesiological masks are widely used, because they are available in every size and for every ethnic group. They are mostly equipped with a standard female 22mm connection. They should be sterilizable and translucent to control the pressure tube.
- Protective masks (full face masks) have to be equipped with a connection fitting to the instrument.

Figure 38. 4-Phase-Rhinomanometers. (A) HRR 2 combined with full-face-mask. (B) HRR 3 with anesthesiological mask.

(A)

(B)

Contemporary diving masks are not suitable for this purpose. The protective masks provide the best warranty against retraction of the skin, the face muscles or the nasal wings, but because of their greater compressible volume they may have an influence on the dynamic properties of the rhinomanometer. Thus, in 4-phase-rhinomanometry, preference is given to the anesthesiological masks.

8.4.2 Pressure tube connection

"The fixation of the pressure tube should not influence the shape of the nasal entrance and should not restrict its mobility during the measurement. Adhesive tape (Microfoam®, 3M) remains therefore the gold standard. Other types of connection should be checked against this tape". This recommendation was part of the first standard of the ISOANA in 1984 and was taken over into the consensus report mentioned above[30]. While most of the other recommendations have been followed by users and producers, it was frequently tried to introduce a "simpler" or "quicker" solution for the safe fixation of the pressure hose, but NOT ANY DEVICE was up to now proofed to be better as the "tape method", but it can be easily demonstrated that plugs as shown in Figure 39 affect every measurement result. The only one exception may be, if the results are labeled with the method of tube fixation, and the measurements are intended to assess nasal congestion as for instance in nasal provocation tests. Use of plugs invalidates completely the results if used for pre-operative assessment of the nose. They block the mobility of the nasal entrance and the functional diagnosis of valve problems. On the other hand, the tape-method has been proven to be quick and reliable as shown in Figure 40. It is simply unnecessary to use any plugs for the connection between tube and nostril.

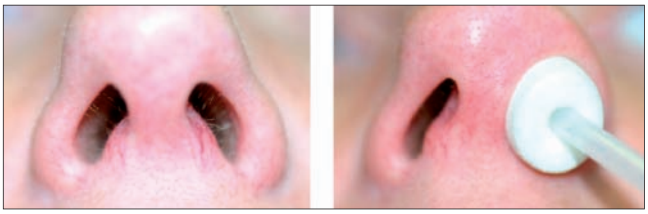
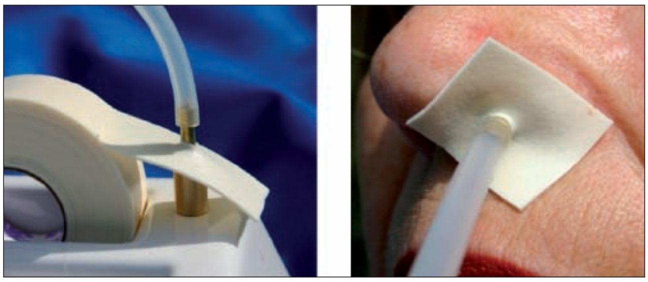


Figure 39. Narrowing of the measured nasal entrance by a commercial plug-adapter.

There are 3 different recommended methods of attaching the pressure tube:

1. The tape method uses commercial adhesive tapes together with plastic or metal connectors. The use of precut, preconfigured adhesive nostril patches, so named "Rhino-patches™", is the most convenient and preferred technique. The patches are designed to fit the shape of the right and left nostrils, come with a self adhesive backing for airtight seal and are preperforated to insert a connector to which the pressure tubing is easily attached. These patches are manufactured of nonsensitizing polyethylene foam and approved for application to the human skin. The same good fixation can be achieved with standard 1"-foam tapes from a dispenser in combination with metal connectors (Figure 40 A, B)

Figure 40. (A) Microfoam™ Tape from a dispenser with (B) perforator connected to the left nostril.



(A) (B)

2. If it is foreseen to perform several measurements in sequence, the pressure hose can be connected with a piece of cannulated Merocel™ Nasal Package (Medtronic, Mystic CN, USA). This method is relatively expensive and needs only be used as in exceptional cases.
3. When planning a more extensive series of examinations with the same patient or examination of nasal respiration during physical excercise, it is recommended to make a silicon stent from dental casting material. Xanthopren H green™ (Bayer Dental, Leverkusen, Germany) with the appropriate hardener has proven especially suitable. Great care must be taken not to deform the nostril(s) when making the cast!!

Thus, one of the most important rules to carry out 4-phase-rhinomanometry is:

Never use a preformed adapter!

There are no ready-made adapters on the market – no matter what material they are made of – that will not deform the nostril if a really airtight seal is required. Preformed adapters are not time saving and will falsify most measurement results!

8-5 Clinical exam before rhinomanometry

As with all functional diagnostic procedures, rhinomanometry cannot by itself substantiate the diagnosis. It is however in a position to objectively assess the patient's symptoms of nasal congestion or obstruction, to disclose connections between morphological findings and subjective adverse effects or to show quantitatively the effects of allergens or drug therapy on the nasal mucous membrane. For these reasons, every rhinomanometric examination must be preceded by a clinical examination of the patient, from which the need of further diagnostic work may become apparent.

The clinical exam should include the following:

8-5-1 History

To assess the nasal ventilatory function, it is necessary to draw

up a special anamnesis, which must include the period, type and possible cause of an impediment in nasal respiration. A self administered standardized questionnaire may be necessary, when a large-scale series of examinations in which several examiners are involved. This can naturally be adapted to include diagnostic problems of particular interest, like questions directed to allergology. The anamnesis must also include any possible lower breathing impediments, e.g. the lungs, which are occasionally included as part of the rhinomanometric examination.
In all cases however, the anamnestic questionnaire should conclude with how the patient assesses his nasal function "now", in order to be able to assess the frequent deviations taking place over the course of a day, which occur in particular in patients with perennial allergies and non-specific hyperreactivity.

8-5-2 Physical exam

Apart from a detailed description of the physical findings within the framework of a pre-operative examination of the nose, it must be determined, prior to the rhinomanometric examination, whether special requirements are demanded of the fitting of the pressure tube. It is important to determine if one nostril is completely blocked or if there is a perforation of the septum. In either case, it is not possible to perform *anterior* rhinomanometry. In addition, details of obvious valve phenomena must not be omitted. Such indications are important to note when the ENT specialist does not perform the examination personally but delegates the task to an assistant.

8-5-3 Preparation of the patient

To perform rhinomanometry, one must ensure that the patient does not use nose drops on the day of examination. The patient must be acclimatised to the temperature of the examination room and be physically rested. The latter requirement is often ignored in the course of a day, under pressure of time. Physical exercise is a reliable method of decongesting the nose: rhinomanometry can thus lead to a better than normal result up to an hour after physical work.
The nose must be free of crusts or secretions. Any secretion present should be removed, as far as possible but without irritation to the nasal mucous membrane.

8-6 Position of the patient

Generally, routine rhinomanometric measurements have to be done in an upright sitting position. The statistical investigations in the chapters above and the consensus report [30] are referring to this position. Changing the position has an obligatory impact to the nasal resistance. It follows, that even in sleep medicine has to be determined the nasal resistance in upright position as the baseline investigation. Nasal resistance increases not only when reclining or laying down, but also – as everybody knows – sometimes when changing the side. Haight and Cole could show that the nasal resistance is not depending on the body position as an influence of gravity but on the skin pressure [69]. In patients with a mucosal hyperreactivity this phenomenon is more frequent. Diagnostic information related to the complaints of the patients can be obtained by the routine decongestion test. Patients, which are complaining about a one-sided blocked nose during sleep in dependency of the sleep position, show frequently a high difference between the temporary resistance (1st measurement) and permanent resistance (2nd measurement).
It should be noticed, that practicable long term measurements methods about the nose during sleep are already commercially available and - after some refinement – will be introduced into the routine of sleep medicine. These methods are semiquantitatively measuring the nasal airflow separately for both sides. They are combined with measurements of snoring, body position or other polygraphic parameters of interest (“Somnowatch”™, Somnomedics, Randersacker, Germany).

8-7 The different rhinomanometric procedures

8-7-1 The Baseline Test (Temporary Obstruction)

The aim of the baseline test is the investigation of the ACTUAL relation between narino-choanal differential pressure and airflow during quiet breathing in one nasal side, both nasal sides separately or in the total nose. This test can be carried out by Active Anterior Rhinomanometry for one nasal side or successively for both sides or by Active Posterior Rhinomanometry for the nose. The diagnostical information of those tests is limited, because one cannot know from this “momentary snapshot”, in which phase of the nasal cycle or under which actual influence of environment or allergens it was taken.

The test it self starts always with the closure of the opposite nostril by the differential pressure hose, and the control of the mask and the tubing for tightness. During the data collection process one should keep in mind, that 4PR is based on the separate control of the pressure and flow channels. In this way, it is easy to see if the breaths have the same shape, which means that they are similar in height and amplitude. The ISOANA recommends to average 3 - 5 breathes within a total uptake time of 15 seconds [30]. They should not differ more than 30% in height and amplitude; otherwise the breathing conditions are different (Figure 41). Some computer programs check the differences and reject exceeding results (HRR2, 3, RhinoLab, Rendsburg, Germany). Due to the possible breathing impediment, which can occur when breathing through one nostril with increased resistance, the patient must be able to breathe freely through the mouth immediately after the measurement has been made. In exceptional cases, anxious patients can be calmed down, if they are told that the measurement procedure only takes a few seconds and that they can terminate at any time, if they "get short of breath".

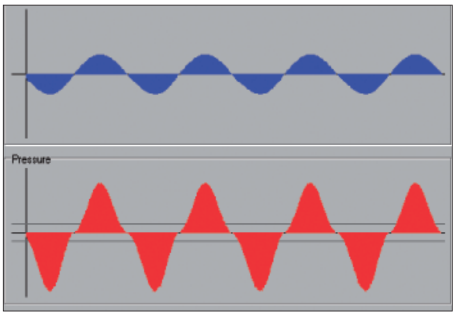


Figure 41. Ideal measurement of 4 breathes.

If a Visual-Analogue-Scale is included in the program, the subjective perception of nasal respiration should be entered for the measured side. After that, the measurement of the second side follows.

Children accept rhinomanometry, if they are allowed to watch each other and the examination takes on the character of a game. By observing their own breathing on the screen, in the form of hills and valleys, computer rhinomanometry becomes a computer game to them.

In rare cases, some patients are not in a position to breathe evenly on command. In such cases, patience is called for to overcome their anxiety. The examination may have to be repeated several days later.

8-7-2 Determining the permanent nasal resistance (Decongestion Test)

To be able to differentiate between a breathing impediment due to turbinal engorgement, irritation or inflammation and that due to a permanent anatomical obstruction, in the majority of all cases, it is necessary to quantify the extent of impediment due to turbinate congestion. This can be done by performing decongestion tests. The degree of congestion of the mucous membrane is reduced either pharmacologically, using decongestant nose drops or by physical exercise.

From the technical point of view, the decongestion test is a follow-up of 2 rhinomanometric measurements, which are depicted in the same graph and compared to each other numerically. The decongestion test can also be used to measure the degree of obstruction after changing the body position, to test a spreader device or to see differences of the nasal resistance in different modes of breathing to see the influence of the nasal valve.

In clinical rhinology, the decongestion test is the default procedure, because it clearly shows the different roles of skeleton and mucosa on to the nasal airway resistance.

8-7-2-1 Decongestion using nose drops

If nose drops are use as a decongestant, which is known as a semi-quantitative test because apart from the type of nose drops used, the amount that is actually effective after application will vary. The application of nose drops per spray is surely the most reliable and the simplest to carry out in the ENT specialist's practice. One must however ensure that the jet of spray from the applicator is not too strong, as this will initiate a physical irritation, which will lead to exactly the opposite of the desired effect. One should pay attention that the nose drops do not contain stabilising substances (benzalkonium chloride), which occasionally can release a severe adverse reaction.

The medicament most often used for decongestion in adults is a 0.1% xylometazoline solution for adults, and for children a 0.05% solution. Following the recommendations of ISOANA, the medicament should be applied immediately after the baseline measurement and after 5 minutes. Comparison measurements shall be carried out 10 minutes after the initial application.

For some reasons the reaction of the nasal mucosa may differ from the normal pattern, and the obstruction before the application of nose drops is of lower degree than after. This can occur during the “switching” of the nasal cycle, because of mechanical irritation of the mucosa by the spray procedure. It is also seen as a symptom of “rhinitis medicamentosa”. An increasing flow above 50% is suspicious to be a sign of specific or non-specific hyperreactivity.

In a routine rhinologic diagnostical procedure, it is useful to follow the decongestion test with an endoscopical investigation to get a summarizing impression that includes anatomical and functional diagnostic aspects.

8-7-2-2 Decongestion by body exercise

Broms [31] found in a comparative study that the decongestion of the nasal turbinates occuring with heavy exercise was more suitable than the application of nose drops to differentiate between the permanent and temporary resistance of the nose. A bicycle ergometer was used to exercise the patients to a heart frequency of 150/min. Disadvantages of this method include the need for exercising and monitoring equipment and the limited application to healthy young subjects. Later, Hasegawa found that the decongestive reaction of the nasal mucosa lasts about 40 min., with an occasional adverse reaction noted [58]. In contrast, Schwarz and Vogt [70] reported that the decongestive reaction using body exercises was less uniform and unpredictable, a reason perhaps why the method is not used as extensively as the “nose drop method”.

8-7-3 Dilatation test and nasal valve diagnosis

One of the advantages of 4-PR is its sensitivity to recognize elastic deformations of the nose during the measurement procedure. If the results of the measurement, the history or the clinical finding are suspicious for a pathological function of the nasal valve, then in addition a subsequent test should be performed under changed breathing conditions. Closure of the nasal valve can be provoked physiologically by high acceleration of the nasal air stream in phase 1, i.e. at the beginning of inspiration. This "sniffing mode" should be imitated by the patient during the "decongestion test", meaning during the second measurement, which has to be done in this case without application of nose drops (Figure 42).

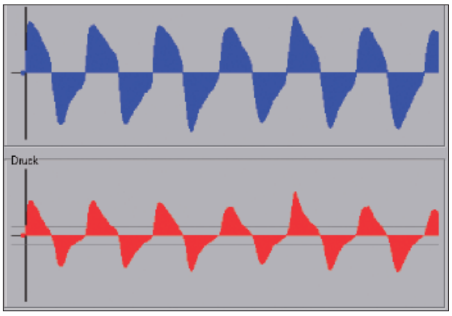


Figure 42. "Sniffing mode" of nasal breathing during the data acquisition. Applying this modification of "Decongestion Test" the influence of the nasal valve becomes clearly visible as shown in Chapter 7.

Basically, to quantify the influence of elasticity of the nasal valve, the diagnostical information by evaluating the 4 different phases of a breathing curve is much more informative than using dilatators. But vice verse, 4PR can be used to test the effect of dilatators, because its effect is much better, if the influence of the nasal valve on to the entire nasal resistance is high (see Chapter 7).

8-7-4 Nasal provocation test (NPT)

The measurement of nasal airflow during intranasal provocation tests enhances the sensitivity and specificity of this important test, which quantifies in situ the effect of an allergen challenge. Therefore, it would be important to follow recommendations of an international or national standard. For Germany, a reliable scoring system is used since 1990 [67]. Unfortunately, currently the literature offers only some suggestions for a correct procedure. Several approaches have been proposed, and their advantages and disadvantages have been described in a summary paper [68].
The NPT can be carried out as a one- or two-sided provocation, with rhinomanometric measurements in one or both sides of the nose. The technical task is the measurement and storage of an unlimited number of measurements in AAR or APR mode, which can be done also on both sides; however, it is recommended that no more than 6 measurements be recorded in the same file.

Please, watch the following basic rules!

1. During a nasal provocation test, 4-PR quantities only one of the symptoms objectively. The mucosal reaction, the severity of the rhinorrhea, sneezing as well as extranasal symptoms have to be evaluated by an experienced allergist.
2. Every provocation test may elicit an anaphylactic reaction. Although rare, the necessary equipment and trained personnel have to be prepared to deal with this emergency situation.

The procedure of the entire investigation is different in a one-sided or two-sided test:

- One sided measurement procedure
  1. Determine the least obstructed or more patent nasal side by simple AAR, without the use of a decongestant.
  2. After application of the active solution (solvent, allergen solution) start a one-side-measurement as procedure and make your first measurement.
  3. Repeat measurements as necessary
  4. Finish the provocation test and record the scores for nasal obstruction, sneezing, itching or other reactions
  5. Print the record if desired

- Double sided measurement procedure
  1. Choose the AAR-mode and NAT as procedure with unlimited repetitions
  2. Make your successive measurements
  3. Finish the test and record the scores as above
  4. Print the record

The provocation test should be finished, if the measured resistance differs by more than 20% from the previous measurement or after 6 subsequent negative tests, because after that the onset of a general irritation effect is very likely.

8-8 Evaluation of clinical measurements

During the introduction of 4-phase-rhinomanometry we have to expect, that many rhinomanometers are still existing, which are based on the standard of 1984 as given by the ISOANA. Records to be included in the patients' documentation therefore should contain beside of the xy-diagram for the "first-view-diagnosis" the measured resp. calculated data for the flow or resistance in 75, 150 and 300 Pa differential pressure. Beside that LVR- and LREFF- Values should be printed out and should be compared with Table 7 for clinical evaluation

It should be repeated, that those values are valid for Caucasian noses before decongestion by drugs or body exercise in a normal temperature and air humidity at sea level. The worldwide collection of clinical data in other ethnical groups has begun and the results will be published continuously.

The first clinical contributions with results obtained from the Chinese mainland population, are the content of the following two chapters.

9. Assessment of Normal Adult Chinese Nasal Airway by Four-Phase Rhinomanometry, Rhinomanometry and Acoustic Rhinometry

Demin Han, Chunting Cao, Luo Zhang

9-1 Introduction

Nasal obstruction is one of the most common complaints in nasal disease. Currently, acoustic rhinometry or (active anterior) rhinomanometry are commonly used to objectively evaluate nasal airway patency. While acoustic rhinometry evaluates the geometry of the nasal cavity by measuring the minimum cross-sectional area (MCA) and nasal volume (NV) [71], rhinomanometry determines the nasal airway resistance by measuring nasal airflow and differential pressure. By dividing the ascending and descending parts of the curves into four parts, four-phase rhinomanometry is considered by the Standardization Committee on Objective Assessment of the Nasal Airway to be a new method of evaluating the patency of the nasal airway [30].

It has been reported that objective nasal measurements show differences among different ethnic groups [72,73], which may be due to different nasal cavity shapes. Therefore, it is crucial to measure the normal nasal range for different ethnic groups, respectively. Until now, no data of objective evaluation of nasal patency among Mainland Chinese has been available in English journals. The aim of our study is firstly, to obtain the values for the three objective methods among the normal adult Chinese, and second, to analyze the correlation among these measurements.

9-2 Materials and methods

9-2-1 subject recruitment

Eighty-five normal adults (170 nasal cavities) including 33 men (66 nasal cavities) and 52 women (104 nasal cavities) were evaluated. The mean age was 37 ± 13 years (range, 18 to 60 years). All subjects were free from nasal symptoms such as nasal obstruction, sneezing and over breathing; had no previous history of chronic nasal disease or nasal operation; had no topical drug administered in the last one month; had no allergic or other severe systemic disease; had no upper respiratory infection in the previous one month, and had no severe septum deviation or other structural abnormality as observed by anterior rhinoscopy. Pregnant and menstruating women and those with acute infections were excluded.

9-2-2 Instruments

Rhinomanometry was performed using the HRR2 four-phase rhinomanometer (RhinoLab GmbH, Rendsburg, Germany) and the ATMOS 300 rhinomanometer (ATMOS MedizinTechnik GmbH & Co., Feldkirch Germany). Acoustic rhinometry was performed using the Eccovision acoustic rhinometer (Hood Labs, Pembroke, USA).

9-2-3 Methods

Measurements were performed in a quiet examination room with a temperature of 24 ± 1°C and a humidity of 70% ± 1%. First, the subjects' height, weight and head circumference (HC) were measured. Body surface area (BSA) and body mass index (BMI) of subjects were calculated by the following formulas:

BSA (m^2) *0.0061×height (cm) + 0.0128 x weight (kg) -0.1529*
and
$BMI = weight / (height / 100)^2$

Subsequently, the subjects sat quietly in the examination room for 20 min and remained sitting upright for measurement. To begin with, the minimum cross-sectional area (MCA) and the volume of 0-5cm of the nasal cavity (NV) were measured by acoustic rhinometry. Next, the effective resistances in inspiration, expiration and the total breathing process (Reffin, Reffex, Refft), and vertex resistance in the process of inspiration and expiration (VRin and VRex) were measured by four-phase rhinomanometry. Finally, the unilateral nasal resistance at a differential pressure of 75 Pa and 150 Pa (R75, R150) were measured by active anterior rhinomanometry. The examination was completed within 6 minutes to maintain a constant congestive state [74].

9-2-4 Statistics

All statistical tests were performed using the SPSS statistical package (version 11.5). All mean values are shown as $\bar{x} \pm$ SD, and an independent-sample t-test was used when two mean values were compared. The correlation coefficient was used to analyze the correlation between the parameters. A value of $p < 0.05$ was considered to be statistically significant.

9-3 Results

9-3-1 Subject characteristics

The means of age, height, weight, head circumference (HC), body surface area (BSA) and body mass index (BMI) of the male and female subjects are summarized respectively in Table 10.

Table 10. Characteristics of the subjects.

	Male (n = 33)	Female (n = 52)
Age (y)	38±14 (18-60)	36±12 (19-60)
Height (cm)	175±5 (164-185)	162±6 (150-181) **
Weight (kg)	71±9 (55-90)	60±9 (45-90) **
HC (cm)	58±2 (55-62)	55±2 (51-59) **
BSA (m^2)	1.94±0.13 (1.71-2.20)	1.72±0.13 (1.49-1.72) **
BMI	23.2±3.1 (18.3-29.4)	22.8±3.3 (16.5-31.3)

** $p < 0.01$

While the mean age and BMI was similar between males and females, the differences in height, weight, HC and BSA between males and females showed statistical significance (all $p < 0.01$).

9-3-2 The measurement of four-phase rhinomanometry

The mean and range of the parameters of four-phase rhinomanometry of different sides of the nasal cavity, as well as the unilateral nasal cavity, are summarized in Tables 11 and 12, respectively. All the parameters were similar between left and right. For each parameter of the unilateral nasal cavity, that of females was higher than for males, but no statistical significance was found among these differences. The correlation coefficients between these parameters and age, height, HC, weight, BSA and BMI are given in Table 13. No statistical significance was found.

Table 11. The measurements of four-phase rhinomanometry of different sides ($Pa/cm^3 \cdot s^{-1}$).

	Left mean (range)	Right mean (range)
Reffin	1.50±1.14 (0.15-4.20)	1.38±0.91 (0.17-3.84)
Reffex	1.58±1.11 (0.30-4.70)	1.66±1.14 (0.19-4.80)
Refft	1.52±1.09 (0.26-4.32)	1.50±0.97 (0.22-4.22)
VRin	1.54±1.14 (0.13-4.43)	1.43±0.92 (0.18-3.78)
VRex	1.61±1.09 (0.29-4.74)	1.74±1.17 (0.22-4.94)

Table 12. The measurements of four-phase rhinomanometry of unilateral nasal cavities ($Pa/cm^3 \cdot s^{-1}$).

	Male mean (range)	Female mean (range)
Reffin	1.28±1.02 (0.15-4.13)	1.55±1.03 (0.17-4.20)
Reffex	1.43±1.07 (0.25-4.70)	1.75±1.14 (0.19-4.80)
Refft	1.34±0.99 (0.22-4.20)	1.62±1.03 (0.22-4.32)
VRin	1.31±1.03 (0.13-4.41)	1.60±1.03 (0.18-4.43)
VRex	1.46±1.04 (0.27-4.74)	1.82±1.17 (0.22-4.94)

Table 13. The correlation coefficients between Reff, VR and age, height, HC, weight, BSA and BMI.

	Reffin	Reffex	Refft	VRin	VRex
Age	− 0.05	− 0.01	− 0.03	− 0.03	− 0.03
Height	− 0.07	− 0.08	− 0.08	− 0.08	− 0.10
HC	− 0.04	− 0.07	− 0.05	− 0.03	− 0.08
Weight	− 0.14	− 0.09	− 0.11	− 0.11	− 0.09
BSA	− 0.13	− 0.10	− 0.13	− 0.13	− 0.10
BMI	− 0.13	− 0.07	− 0.11	− 0.11	− 0.06

9-3-3 Measurement of Rhinomanometry and acoustic rhinometry of unilateral nasal cavities

Out of the total of 170 nasal cavities measured, the differential pressure of 155 nasal cavities (91%) reached 75 Pa and the nasal resistance was obtained at this point. In only 92 nasal cavities (54%) could a differential pressure of 150 Pa be reached and the nasal resistance obtained at this point. The mean and range of measurements by traditional rhinomanometry and acoustic rhinometry of unilateral nasal cavities are summarized in Table 14. Other than for R150, the differences in mean value between men and women all show statistical significance ($p = 0.012$ for R75; $p = 0.004$ for minimal cross-sectional area (MCA); $p = 0.002$ for nasal cavity volume (NV)).

Table 14. Mean and range of acoustic rhinometry and rhinomanometry of unilateral nasal cavities.

	Male mean (range)	Female mean (range)
R75 ($Pa/cm^3 s^{-1}$)	0.31±0.17(0.12-0.98)	0.39±0.18 (0.15-0.94) *
R150 ($Pa/cm^3 s^{-1}$)	0.56±0.25(0.29-1.30)	0.62±0.26 (0.20-1.40)
MCA (cm^2)	0.62±0.18(0.21-0.97)	0.54±0.15 (0.18-0.87) **
NV (cm^3)	5.20±1.57(1.86-8.90)	4.42±1.29 (2.04-8.46) **

*$p < 0.05$, ** $p < 0.01$

The correlation coefficients between the mean value and age, height, HC, weight, BSA and BMI are shown in Table 15. Statistically significant correlation was found between R75 and age, weight, BSA and BMI ($p = 0.009$ for age; $p = 0.002$ for weight; $p = 0.003$ for BSA; $p = 0.023$ for BMI). No statistically significant correlation was found between R75, height, and HC. No statistically significant correlation was found between R150 and age, height, HC, weight, BSA and BMI. Statistically significant correlation was found between the MCA, NV and age ($p = 0.019$ for MCA; $p = 0.001$ for NV), and no statistically significant correlation was found between MCA, NV and height, HC, weight, BSA and BMI.

Table 15. The correlation coefficients between R75, R150, MCA, NV and age, weight, HC, weight, BSA, BMI.

	R75	R150	MCA	NV
Age	− 0.23**	− 0.12	0.19*	0.26**
Height	− 0.16	− 0.10	0.04	0.15
HC	− 0.08	− 0.08	0.06	0.15
Weight	− 0.26**	− 0.14	0.02	0.07
BSA	− 0.26**	− 0.15	0.03	0.10
BMI	− 0.20*	− 0.10	0.02	0.00

* $p < 0.05$, ** $p < 0.01$

9-3-4 Correlation among different measurements

First, the correlation coefficients between the parameters of four-phase rhinomanometry and those of traditional rhinomanometry are shown in Table 16. Each comparison has statistical significance. Secondly, the correlation coefficients

Table 16. The correlation coefficients of four-phase rhinomanometry and the measurement of rhinomanometry.

	Reffin	Reffex	Refft	VRin	VRex
R75	0.43**	0.34**	0.41**	0.39**	0.30**
R150	0.39**	0.34**	0.37**	0.33**	0.27*

* $p < 0.05$, ** $p < 0.01$

Table 17. The correlation coefficients of four-phase rhinomanometry and the measurement of acoustic rhinometry.

	Reffin	Reffex	Refft	VRin	VRex
MCA	− 0.19*	− 0.19*	− 0.19*	− 0.18*	− 0.16
NV	− 0.20*	− 0.19*	− 0.20*	− 0.20*	− 0.18*

* $p < 0.05$

Table 18. Correlation coefficients of rhinomanometry and acoustic rhinometry.

	MCA	NV
R75	− 0.18*	− 0.29**
R150	− 0.16	− 0.31**

** $p < 0.01$

between the parameters of four-phase rhinomanometry and those of acoustic rhinometry are shown in Table 17. All these correlations have statistical significance except for VRex and MCA. Finally, the Pearson correlation coefficients between the parameters of traditional rhinomanometry and those of acoustic rhinometry are shown in Table 18. Statistically significant correlation was found except for R150 and MCA.

9-4 Discussion

We measured 85 normal adult Chinese by four-phase rhinomanometry, rhinomanometry and acoustic rhinometry in order to obtain the normal values for Chinese noses in the natural congestive state. As some differences between our subjects and other ethnic groups in height, weight and body mass index were found in the literature [75,76], it was considered necessary to obtain the normal values for Chinese.

In hydromechanics, when air flows through the nasal cavity, its resistance is equal to the ratio between differential pressure and airflow velocity ($R=\triangle P/V$). With regard to the changes in differential pressure and airflow velocity, the whole breathing cycle can be divided into four phases, which are an increase in the inspiration phase, a decrease in the inspiration phase, an increase in the expiration phase, and a decrease in expiration. While traditional rhinomanometry focuses on the average resistance at a point of certain differential pressure, four-phase rhinomanometry takes the increasing and decreasing phases of the breathing cycle into consideration. Therefore, it may provide us with more information about nasal airflow. Four-phase rhinomanometry offers two new parameters: effective resistances (Reff) and vertex resistance (VR). Reff is equal to the effective value for the pressure gradient divided by the effective value for flow, and these "effective values" for flow, and the pressure gradients are calculated by averaging the values at predetermined equal time segments and dividing the integral by the number of those segments. VR is the resistance determined at the point of maximal flow.

Based on our measurements of normal Chinese, the left and right sides of the nasal cavity had similar mean Reff and VR. The Reff and VR have no significant correlation with age, height, head circumference (HC), weight, body surface area (BSA) and body mass index (BMI). Meanwhile Reff and VR are correlative, and the correlation coefficients during the inspiration and expiration phases are all larger than 0.98, almost a linear relationship.

Nasal differential pressure and airflow velocity are in a nonlinear relationship. In order to make the results of rhinomanometry more comparable, the International Committee on Standardization of Rhinomanometry (ISOANA) proposed anterior active rhinomanometry as the internationally universal method in 1984, with the measurement result expressed as the nasal resistance at 150 Pa differential pressure [4]. Some researchers have suggested that the nasal differential pressure of many subjects during peaceful breathing could not reach 150 Pa (2). In our study, only 54.1% of nasal cavities' differential pressure could reach 150 Pa, while 91% of nasal cavities reached 75 Pa. Therefore, in our opinion, using the resistance at the 75 Pa point to represent the nasal resistance is more reasonable for Chinese subjects.

Ohki et al. [78] found ethnic differences in nasal resistance among normal young Caucasian, Oriental, and Negro adults. A study from England reported that the mean unilateral nasal resistance at the 150 Pa point was 0.65 Pa/cm^3/s [79]; Suzina et al. [77] measured 85 normal adult Malays by anterior active rhinomanometry and reported that the unilateral nasal resistance was 0.46 Pa/cm^3/s at 75 Pa and 0.51 Pa/cm^3/s at 150 Pa. They also found height had a significant negative correlation with the total resistance, but no significant correlation between age, weight and nasal resistance, and no gender difference was found. A study from Finland analyzed 332 normal subjects aged 16-82 years by posterior rhinomanometry. They found nasal airflow rate and nasal pressures increased with increasing body mass index (BMI), and that mean values of airflow rate and pressures were significantly higher in males than in females, but age was not associated with airflow rate or nasal pressure [80]. Numminen et al. [81] examined 249 healthy white subjects, 171 women and 78 men, by rhinomanometry and found BMI and age had no influence on the results.

In our study, the mean R75 of females was higher than that of males, but there was no gender difference at R150. One reason for this finding may be that the number of subjects who could achieve the higher pressure was not large enough; another reason may be that the men who could reach such a pressure were those with larger nasal resistance, which reduced the difference between men and women. To some extent, this was similar for children [82-84]. We found a negative correlation between R75 and age, and this was different to many studies of subjects of other ethnic groups. R75 also showed a negative correlation with weight, body surface area (BSA) and BMI, and this seemed in accord with the positive correlation between vital capacity and BMI, which was known by all, but this trend could not be found at R150. Again, this may be due to the fewer subjects reaching this pressure.

We found that the variation between the maximal and minimal nasal resistance is about 8 times in males and 6 times in females at the pressure difference of 75 Pa, and about 4 times in males and 7 times in females at 150 Pa, while the variation in normal values of four-phase rhinomanometry is broader, in some cases more than 20 times. Therefore, the influence of variation in nasal geometry and congestion on the measurement by four-phase rhinomanometry is larger than that by traditional rhinomanometry measurement.

Some researchers have studied the influence of ethnicity on measurements obtained by acoustic rhinometry. Morgan et al. [73] reported that the mean minimum cross-sectional area (MCA) of the right and left nasal cavities of Orientals, Caucasians and Negroes are 0.63 cm^2, 0.69 cm^2 and 0.87 cm^2 respectively, showing significant ethnic differences between Orientals, Caucasians and Negroes. They also found significant ethnic differences in nasal volume (0-4 cm) in both decongested and non-decongested noses. Huang et al. [86] evaluated the mean MCA and total volume of 1-5 cm of the nasal cavity (NV) in Chinese, Malays and Indians by acoustic rhinometry, and found no difference between these groups. The mean MCA of the Chinese subjects they measured was 0.75 cm^2, which was larger than we found in the current study, possibly because of the different analyses segment. Corey et al. [72] measured the normal value by acoustic rhinometry of Asian, white and black subjects and found ethnic differences between the black group and the other two groups in the first MCA both before and after decongestion; no ethnic difference was found in NV. They also found that sex, height and weight have no effects on the results for all ethnic groups. Burres [87] measured 28 Asians aged 21-58 years by acoustic rhinometry, finding the unilateral MCA to be 0.56 cm2, which is similar to our finding. Gurr et al. [88] examined the differences between Indian and Anglo-Saxon noses and found that MCA and NV between 0-6 cm show no significant differences between the two groups.

In children, most studies show that with increasing age, NV and MCA measured by acoustic rhinometry also increased [91,92], but the effects of age as well as weight, height, HC, BMI and BSA on the measurements for adults were controversial. A study from Sweden analyzed 334 normal individuals aged 4 to 61 years and found MCA correlated weakly to weight, height, age and BMI [92,93]. Kalmovich et al. [94] analyzed 165 subjects aged 20-93 years and found the nasal volume between 0-7cm and the first two MCAs increase significantly with age, except for men over 80 years. Jurlina [95] found a statistically significant difference between the BSA and MCA, but age had no significant effect on the value of MCA. Tomkinson et al. [25] found MCA had a significant correlation with both the nasal alar breadth and the nasal triangular area, but no significant correlation was found with height, weight, facial width and facial height. In our study, MCA and NV had a positive correlation with age, which accorded with the declining trend of nasal resistance with increasing age, and this trend may be caused by the change in nasal appearance with age [97]. We failed to find a significant correlation between MCA and NV and height, HC, weight, BMI and BSA.

Rhinomanometry and acoustic rhinometry are two of the most widely used objective methods for evaluation of nasal patency, and the correlation between them has been studied previously [53,98-101]. Most of the studies revealed a significant correlation between the results of the two methods. Four-phase rhinomanometry is a relatively new technique, and the literature concerning the correlation between it and traditional rhinomanometry or acoustic rhinometry is sparse. In the current study, we found a significant correlation between R75 and MCA and NV, as well as between R150 and NV, which was similar to most of the previous studies of noses in other ethnic groups, but no correlation was found between R150 and MCA. Part of the reason for this is that only about half of the nasal cavities (54%) could reach 150 Pa differential pressure. With the results of four-phase rhinomanometry, both Reff and VR had a significant positive correlation with the traditional rhinomanometry results (R75, R150). For the subjects whose nasal resistance could not reach the 150 Pa point, four-phase rhinomanometry was a good complement to traditional rhinomanometry. A significant negative correlation was also found between Reff, VR, MCA and NV, except for VRex and MCA.

In summary, it is necessary to obtain the normal values of objective nasal measurement of persons of different ethnicity. Among the normal adult Chinese, the results of four-phase rhinomanometry show significant correlation to those of traditional rhinomanometry as well as acoustic rhinometry, and this new technique is complementary to those methods.

10. Four-phase rhinomanometry and acoustic rhinometry in the evaluation of nasal patency of Chinese with nasal septal deviation

Chunting Cao, Demin Han, Luo Zhang

10-1 Introduction

Rhinologists have long been searching for reliable methods to objectively evaluate nasal patency in patients with nasal complaints. Generally speaking, rhinomanometry, acoustic rhinometry, and nasal peak flow, as well as nasal spirometry (102) are all valuable objective instruments for the evaluation of subjective nasal obstruction (103). While acoustic rhinometry provides information on the geometry of the nasal cavity through a static procedure, by measuring the cross-sectional area and nasal volume (NV) as a function of distance from the nostril (71,104), rhinomanometry measures nasal resistance to respiratory airflow through a dynamic procedure, by calculating nasal airway resistance in expiration and inspiration at different reference pressures according to the formula $\Delta p/\Delta V$ (30,105). Both of these objective methods of measurement have been validated, and comparative studies have indicated correlations between nasal airflow resistances and nasal airway volumes in both healthy controls (81) and patients complaining of nasal obstruction (105,106).

By further dividing inspiration and expiration into increasing and decreasing phases, four-phase rhinomanometry (High Resolution Rhinomanometry, HRR) developed by Vogt et al. (32) in 1993, may provide supplementary information because of the separated ascending and descending parts of the curves during inspiration and expiration (30,110). Two new parameters were introduced: effective resistance (Reff), which is equal to the effective value for the pressure gradient divided by the effective value for flow, and vertex resistance (VR), which is the resistance determined at the point of maximal flow. Recently, four-phase rhinomanometry was recommended as the universal standard by the Standardization Committee on Objective Assessment of the Nasal Airway (ISOANA) (30). However, four-phase rhinomanometry has not previously been published sufficiently as an objective assessment of patients with nasal obstruction in a population of mainland China.

Nasal obstruction is one of the most common nasal symptoms caused by inflammation or trauma, as well as by structural abnormalities such as nasal septal deviation (NSD). It is crucial to objectively evaluate nasal patency in patients with NSD in order to accurately determine the severity of the symptoms. The aim of this study was to compare nasal airflow resistance by four-phase rhinomanometry with nasal airway volumes by acoustic rhinometry in symptomatic and asymptomatic Chinese with NSD.

10-2 Materials and methods

10-2-1 Subject recruitment

A total of 72 subjects took part in the study from October 2005 to December 2006, including 30 patients (25 males and 5 females with an average age of 34 years, ranging from 19 to 57 years) suffering from nasal obstruction due to nasal septal deviation (NSD), 25 asymptomatic subjects with deviated nasal septa (21 males and 4 females with an average age of 38 years, ranging from 19 to 59 years) and 17 healthy controls (34 sides; 14 males and 3 females with an average age of 35 years, ranging from 18 to 60 years) with a normal nasal cavity appearance by anterior rhinoscopic examination. Criteria for inclusion of a subject in the study were 1) $>$ 18 years of age, 2) no previous history of nasal operation, 3) absence of acute upper respiratory tract infection in the preceding 2 weeks, 4) absence of the application of any topical drugs in the preceding 1 month, and 5) absence of significant systemic disease. Written informed consent was obtained from all subjects. The study was approved by the Ethics Committee of the Beijing Institute of Otolaryngology.

All subjects assessed the severity of their nasal obstruction on a 100 mm visual analog scale (VAS), where 0 mm represented no obstruction and 100 mm represented maximum obstruction. The diagnosis of NSD with no other nasal cavity or sinus disease or abnormal nasal structures was made by anterior rhinoscopy and sinus computed tomography (CT). All subjects had normal mucous membranes and no chronic respiratory tract infection. The healthy controls and asymptomatic subjects had no symptoms of nasal trouble such as nasal obstruction (VAS of nasal obstruction for these subjects was 0).

10-2-2 Measurements

The subjects were asked to sit quietly in the laboratory (temperature, 22 - 24° C; humidity, 40% - 70%) for 20 min and remained sitting upright for measurement. While both sides of the nasal cavity of healthy control subjects were measured, only the deviated narrow side was measured for those subjects with nasal septal deviation (30 sides for symptomatic subjects and 25 sides for asymptomatic subjects). First, minimum cross-sectional area (MCA) and the volume of 0-1 cm, 1-2 cm, 2-5 cm and 5-7 cm of each nasal cavity (V1, V12, V25 and V57) were measured by acoustic rhinometry (Ecco Vision; Hood Laboratories, Pembroke, MA, USA). Secondly, the effective resistances in inspiration and expiration (Reffin, Reffex), as well as vertex resistance in the process of inspiration and expi-

Table 19. Four-phase rhinomanometry measurements (Pa/cm^3·s^{-1}, ±sd)

Subjects	n	Reffin	Reffex	VRin	VRex
NSD patients	30	2.52±2.30	2.71±2.55	2.62±2.36	2.75±2.51
Asymptomatic patients	25	1.32±1.16	1.57±1.38	1.34±1.71	1.62±1.42
Healthy controls	17	1.04±0.83	1.02±0.41	1.13±0.99	1.06±0.38

NSD = nasal septum deviation

ration (VRin and VRex) were measured using the HRR2 four-phase rhinomanometer (RhinoLab GmbH, Rendsburg, Germany). The examination was completed within 6 minutes to maintain a constant congestive state.

10-2-3 Statistics

Data are expressed as means ± S.D. All statistical tests were performed using the SPSS statistical package (version 11.5). As the data were normally distributed, the statistical significance of the differences was assessed with Student's t-test and Pearson's correlation coefficient. A value of $p < 0.05$ was considered significant.

10-3 Results

10-3-1 Four-phase rhinomanometry

The measurements are summarized in Table 19. For the mean values of effective resistance and vertex resistance in inspiration and expiration (Reffin, Reffex, VRin and VRex), significant differences were found, either between patients with nasal septal deviation (NSD) and asymptomatic subjects, respectively (p = 0.009 for Reffin; p = 0.023 for Reffex; p = 0.008 for VRin; p = 0.023for VRex) or between symptomatic patients and healthy controls, respectively (p = 0.015 for Reffin; p = 0.007 for Reffex; p = 0.020 for VRin; p = 0.005 for VRex). Meanwhile, no significant differences were found between asymptomatic subjects and healthy controls.

10-3-2 Acoustic rhinometry

The measurements are summarized in Table 20. For the mean values of the volume of 0-1 cm, 1-2 cm, 2-5 cm and 5-7 cm of each nasal cavity (V1, V12, V25 and V57), minimum cross-sectional area (MCA) and the distance from the nostril to the minimum cross-sectional area (MD), significant differences were found in V25, V57 and MD, respectively, but not in V1, V12 and MCA, either between symptomatic and asymptomatic subjects with NSD (p = 0.013 for V25; p = 0.005 for V57; p = 0.000 for MD) or between patients and healthy controls, respectively (p = 0.045 for V25; p = 0.027 for V57; p = 0.017 for MD). Meanwhile, no significant differences were found between asymptomatic NSD subjects and healthy controls.

10-3-3 The correlation between four-phase rhinomanometry and acoustic rhinometry measurements in NSD patients

Of 30 patients with NSD, the Pearson's correlation coefficients between the parameters of the two measurements are summarized in Table 21. The Reffin, Reffex, VRin and VRex were significantly correlated to V12, V25, V57 and MCA, respectively, with only V1 showing no significant correlation.

Table 21. The correlation coefficients of four-phase rhinomanometry and acoustic rhinometry measurements

	V1	V12	V25	V57	MCA
Reffin	0.216	0.552**	0.557**	0.393*	0.569**
Reffex	0.267	0.480**	0.494**	0.383*	0.479**
VRin	0.201	0.510**	0.559**	0.386*	0.564**
VRex	0.259	0.472**	0.502**	0.392*	0.493**

**P<0.01, *P<0.05

10-3-4 The correlation between visual analog scores (VAS) and four-phase rhinomanometry and acoustic rhinometry

No significant correlation was found between the VAS and each parameter of four-phase rhinomanometry and acoustic rhinometry, respectively, except for V25 (r = -0.382, p = 0.037).

10-4 Discussion

Nasal obstruction caused by nasal septal deviation (NSD) is a major diagnostic challenge for the rhinologist because of its frequency and the complexity of choice for its treatment. It is not rare for the subjective feeling of impaired nasal breathing, a symptom of nasal obstruction, to be inconsistent with the appearance of the nasal cavities. Therefore, objective criteria are required for accurate diagnosis, staging of pathology and correct choice of treatment. Acoustic rhinometry is an objective assessment of the structural anatomy of the nasal cavity, which detects the acoustic signals reflected from the wall of

Table 20. Acoustic rhinometry measurements ($\bar{x}$ ± sd)

	n	V1(cm^3)	V12(cm^3)	V25(cm^3)	V57(cm^3)	MCA(cm^2)	MD(cm)
NSD patients	30	0.84±0.12	0.81±0.19	2.65±1.12	2.71±0.94	0.52±0.24	2.13±0.45
Assymptomatic patients	25	0.82±0.17	0.83±0.26	3.47±1.27	3.77±1.60	0.62±0.17	1.44±0.84
Healthy controls	17	0.81±0.21	0.83±0.21	3.45±1.37	3.59±1.42	0.59±0.17	1.48±0.94

the nasal cavity. The valuable parameters of the measurement are minimum cross-sectional area (MCA), volume of the nasal cavity (NV), and the distance from the nostril to the minimum cross-sectional area (MD). This method of measurement has been validated against other objective modalities [104,108,109]. In our study, the MCA and NV of the healthy controls were within the range of the reference values from a greater number of subjects (85 cases, data not shown) and close to that of Thai noses [89], and the acoustic rhinometry was sufficiently sensitive to reveal symptomatic NSDs (volume of 2-5cm and 5-7 cm of the nasal cavity (V25, V57) and MD) compared to asymptomatic NSD. However, we, in accordance with Tantilipikorn et al. [89], found acoustic rhinometric measurement was not sensitive enough to differentiate asymptomatic subjects with NSD from healthy controls, since there were no significant differences in the mean of the MCA and NV between the two groups. Meanwhile, only V25 correlated with subjective visual analogue scores (VAS) in symptomatic patients.

By contrast with static acoustic rhinometry, a non-physiological measure of nasal patency detecting the acoustic signals reflected from the wall of the nasal cavity, rhinomanometry, a dynamic technique, results in a parameter known as nasal resistance from interpretation of the nasal flow-pressure relation curve and contributes much to the understanding of nasal airflow physiology [30]. Currently, it is considered the gold-standard for the objective assessment of nasal patency. Correlations have been reported between conventional rhinomanometry and subjective sensation (VAS) [107], as well as acoustic rhinometry [105,106]. In patients with different nasal pathologies who complained of nasal obstruction, both conventional rhinomanometry and acoustic rhinometry were applied to objectively evaluate nasal patency [53,106,111]. It has been generally accepted that these two widely-used complementary techniques can provide valuable guidance in the management of symptoms of nasal obstruction [81,112]. However, the correlation of the newly-developed technique of four-phase rhinomanometry and acoustic rhinometry has not previously been investigated.

Four-phase rhinomanometry separates the ascending and descending parts of the pressure-flow curves during inspiration and expiration, which may provide supplementary information [30]. Our results have shown that four-phase rhinomanometry was sufficiently sensitive to differentiate patients with septal deviation from asymptomatic subjects and healthy controls, respectively (effective resistance and vertex resistance in inspiration and expiration (Reffin, Reffex, VRin and VRex)). Moreover, nasal airflow resistances described as Reffin, Reffex, VRin and VRex were significantly correlated to MCA and NV (V12, V25, V57), except the NV of 0-1 cm (V1), the most anterior volume of the nasal cavity, in non-decongested noses with complaints of obstruction. This is in accordance with Zhang et al. [106] who also reported similar results by using active posterior rhinomanometry and acoustic rhinometry. Our data indicated that the parameters of four-phase rhinomanometry have close correlations with the NV 1cm behind the nostril, and especially the volume of 2-5 cm. Therefore, the nasal resistance will increase when the septal deviation has influence on the volume of 2-7 cm (V27), especially the volume of 2-5 cm. However, if the deviation is not considerable enough to influence V27 (especially V25), the nasal resistance will not significantly increase.

On the other hand, no parameter of the four-phase rhinomanometric measurements correlated with the subjective VAS. The correlation between objective and subjective measurements of nasal patency might be influenced by the measurement technique, the application of decongestants, the presence of nasal disease (septal deviation and nasal polyps) and the location of the NSD. By using posterior rhinomanometry, Tomkinson and Eccles [51] did not demonstrate a significant correlation between nasal resistance and VAS in healthy controls. Roithmann et al. [53] found correlations either between rhinomanometry and acoustic rhinometry or between rhinomanometry and VAS in patients with nasal obstructions by using a head-out body plethysmograph. Szucs and Clement [105] reported a correlation between nasal resistance measured by active anterior rhinomanometry and VAS in patients with NSD. Meanwhile, both rhinomanometry and acoustic rhinometry were more sensitive in revealing deviations in the anterior nasal cavities. Kjærgaard et al. [113] also reported an association between VAS and physiological nasal parameters measured by peak nasal inspiratory flow and acoustic rhinometry. Due to the limited number of subjects in each of the three groups, the lack of the location of the NSD, and the absence of application of decongestants, the clarification of the correlation of subjective and objective measurement and its related influencing factors is beyond this study. A future study of a larger number of subjects, together with detailed description of the subjects, could provide further insight into this area.

In summary, four-phase rhinomanometric nasal airflow resistances are sensitive enough to differentiate symptomatic patients with NSD from asymptomatic subjects and healthy controls. The objective techniques for evaluating nasal patency of subjects with NSD, four-phase rhinomanometry and acoustic rhinometry, have significant correlation and should be performed together to provide insight into the physiology and anatomy of nasal airflow.

11. References

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