ADDENDUM

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Consensus report on acoustic rhinometry and rhinomanometry [1]*

P.A.R. Clement and F. Gordts
ENT Department, Academisch Ziekenhuis, Vrije Universiteit Brussel, Brussels, Belgium

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

FOUR PHASES RHINOMANOMETRY

A more recent and experimental development is the **four phases rhinomanometry** [2, 3] (Figure 1). The participants of the present Consensus Conference agreed that the term four phases rhinomanometry is a more accurate description of this recording technique than "high resolution rhinomanometry". Four phases rhinomanometry might provide supplementary information because of the separated ascending and descending parts of the curves during inspiration and expiration. All members of the Standardisation Committee agree that it is useful to study the ascending and descending parts of the curve separately, and this with respect to movements of the lateral nasal wall of the nasal vestibule during breathing. However, some members wonder how far the observed phase shift is due to the equipment used and/or the unphysiologically high pressures generated during the forced respiration necessary to obtain four phases rhinomanometry. On the other hand, typical aspects for four phases rhinomanometry such as the "hysteresis" with the curves not passing through the x- and y-axis

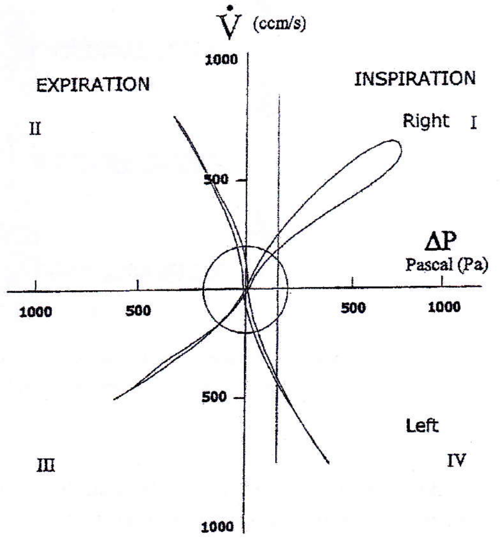

Figure 1. Four phases rhinomanometry.

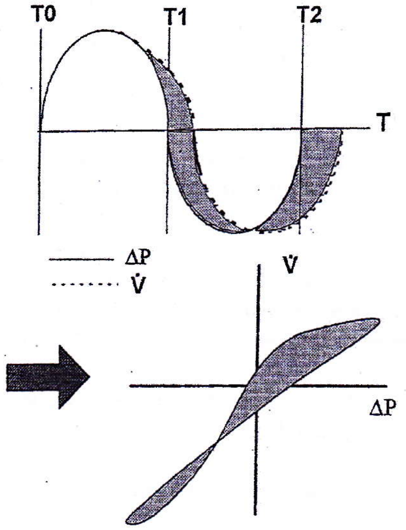

Figure 2. Phase shifting between differential pressure and flow in nasal airflow.

intersection, could be explained as follows: during cyclical nasal breathing, a phase shift is typically observed between the flow and differential pressure, when both are measured as a function of time. This phase shifting is a part of the characteristic behaviour of the nasal air-stream, and is not only an artefact caused by the rhinomanometer [2]. It follows that the general form of the rhinomanometric curve does not correspond to a simple S-shaped bent line through the intersection of the x- and y-axis but to a double loop crossing both axis outside of the intersection point (Figure 2).

The physiological phase shifting between pressure and flow is caused by:

- the inertia (acceleration) of the streaming air
- the elasticity (deformation) of the nasal structures

The influence of the inertia can be described by a formula derived by Hoffrichter [2]:

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$$V°(t)^2 = 2A^2 \Delta p/\rho - 2V\, dV°/dt$$

in which A = cross-section area, ρ = density of air, V = volume, dV°/dt = acceleration.

As to the equation, the nasal airflow is higher with increasing cross-section area A and with increasing differential pressure according to by Bernouilli's law. However, the airflow is diminished at an amount, which depends on the streaming volume and its acceleration within the nasal channel. The higher the streaming volume within the stream obstacle, the higher the influence of the second term in Hoffrichter's equation.

The influence of the inertia of the air and the consequences on the relation between pressure and flow during changing pressure from expiration to inspiration is shown in Figure 3. At T0 a differential pressure generates an outwards-directed flow. At T1 the pressure in the nasopharynx is suddenly interrupted furthermore. At that time the volume in the tube-like nose is flowing furthermore with undiminished speed as long as the kinetic energy of the accelerated gas is not consumed by friction within the tube. At T2, at the beginning of the reversal of the pressure, the flow is still directed outwards but diminished. In T3, when the pressure is already effective negative ("inspiratory"), the flow in the nose stops for a short moment. The flow towards the inspiratory direction starts not before T4.

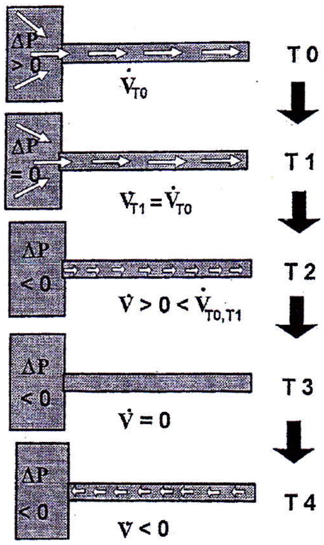

Figure 3. Relation between pressure and flow during reversing differential pressure from expiration to inspiration.

The second cause of phase shifting and hysteresis of the curves is the fact that the nose normally changes its form under the influence of the nasal air-stream by different amounts due to the elasticity (deformation) of anatomical structures. Some causes of deformation like alar collapse are relatively large and won't be missed, while others that occur within the nose are much more subtle. Deformation is equivalent to capacity: a part of the energy on deformation is stored and afterwards restored (this causes a phase shift of + 90°). The influence of these dynamic changes of the nose by elastic air-stream induced deformation cannot be calculated by a mathematical model, but it can be described individually by detailed imaging of the 4 parts of the nasal breathing cycle in four phases rhinomanometry.

One parameter that tells whether or not the periodic nature is of importance, is the Womersley parameter, defined as follows, for a cylindrical channel of radius r:

$$W = r\sqrt{\omega/\nu}$$

in which ω = respiratory pulsation $=2\pi f$, where f is the frequency and ν = kinematic viscosity of the air= 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 air $\nu = 15.10^{-6}$, the Womersley number is

$$W \sim 375\, r \sim 1.9 \qquad \text{for a radius of 5 mm}$$

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 effects 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

$$\Delta p = ZQ$$

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

$$Z = R + j\omega L + 1/j\omega C \qquad j=\sqrt{-1} \text{ is the imaginary unit}$$

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

$$R = 8\,\rho v/(\pi\, r^4)$$

$$C = 2\pi\, r^3/hE$$

$$L = \rho/(\pi\, r^2)$$

h = thickness of the membrane , E = elasticity modulus of the membrane, ρ = density of 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 part of Z will give the phase shift.
It is important to notice that this impedance has also to be applied to the elastic tubes of the measuring equipment.
Conclusions: The influence of the hardware of the rhinomanometry equipment, and especially that of the mask, are probably of greater importance on the hysteresis of the curves than that of the nose itself. The hysteresis has three possible causes:

1. the equipment (can be corrected although more difficult for the mask)
2. inertia
3. nasal valve (has less influence during expiration than during inspiration)

Also, the resonance frequency is of importance, especially since it is different for measurements of the flow and the pressure.
Despite having all physical data to hand, some unknown factors still remain. However, these factors are probably not important for daily clinical practice.

REFERENCES

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