Correlation of nasal morphology and respiratory function*

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SUMMARY

In order to investigate the fluid dynamic preconditions that guarantee a sufficient contact of air with nasal mucosa, we studied flow patterns in modified "Mink's boxes" and in nasal models.

As a result, the nose can be divided into 1) a functional area, i.e. area of turbinates, 2) an inflow area, i.e. vestibulum, isthmus and anterior cavum and 3) an outflow area, i.e. posterior cavum, choanae and epipharynx. The vestibulum is shaped like and acts as a bend, redirecting air to the cavum, and as a nozzle, reducing turbulence. With its concavely curved shape, the isthmus facilitates equal distribution of air throughout the entire area of the turbinates. The anterior cavum acts as a diffuser, where turbulence increases and velocity decreases.

In the slit-like space of the area of turbinates, the flow behavior is determined by flow dynamics in the inflow area. The structure elements of the outflow area are similar to those of the inflow area but lined up in an inverse order.

Key words: nasal physiology, nasal morphology, nasal airflow, laminar flow, turbulent flow

INTRODUCTION

The respiratory function of the nose is considered to be a tempering, humidifying and cleaning mechanism for the inspired air. Thus, the nose is not just a passive organ allowing the air to pass through it, but a complex structure setting part of the prerequisites for an optimal alveolar gas exchange. It is unknown, however, how sufficient contact of all particles with nasal mucosa is realized. Flow dispersion and stream behavior of the air running through the nasal cavum seem to be of enormous importance. Many investigators have tried to elucidate the dynamics of nasal airflow (Burchardt, 1905; Mink, 1920; Tonndorf, 1939; Proetz, 1951; Proetz, 1953; Fischer, 1967; Masing, 1967; Levine et al., 1986; Hornung et al., 1987; Kayser, 1989; Naito, 1989; Hess et al., 1992; Mlynski et al., 1993).

Our knowledge, how optimal contact between particles and the entire mucosa is guaranteed is still insufficient. The aim of our experiments was to investigate the influence of nasal morphology as the most important parameter of stream mechanics determining nasal air flow.

MATERIALS AND METHODS

A detailed description on the construction of our models and the experimental equipment can be found in Mlynski et al. (2000). In short: Experiments were done on modified "Mink's boxes" (Mink, 1920) and on nasal models. Mink's boxes were made of transparent plastic and measured 5 x 8 x 0.6 cm. Similar to the nose, inflow and outflow openings were positioned at the inferior anterior part and the inferior posterior part of the box, respectively. The boxes had no structured inner spaces. Thus, the flow only followed inflow and outflow conditions. In order to study the influence of special structures on flow, the inner space of the boxes could be altered by placing these structures into the boxes.

Transparent models of the human nose were constructed by taking casts from human cadavers and from living human beings.

Water was run through the models. Fluid velocity was measured and converted into air velocity using Reynolds' law. Numbers for flow velocity used in this paper indicate the calculated airflow in ml/s. An advantage of using water is the about 13-fold decrease in flow velocity compared to air. Thus, stream behavior was easier to observe.

The opening for the outflow was connected to a suction pump. The models were immersed in a huge water reservoir. That way flow through the models was similar to that in the nose, where negative pressure in the pharyngeal space causes airflow out of a huge air space unrestricted into the nose.

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Flow was then visualized with the help of traces of dye injected into the water. Careful attention had to be taken, that the velocity of the injected dye was the same as the velocity of inflowing water.
The experimental set up is illustrated in Figure 1.

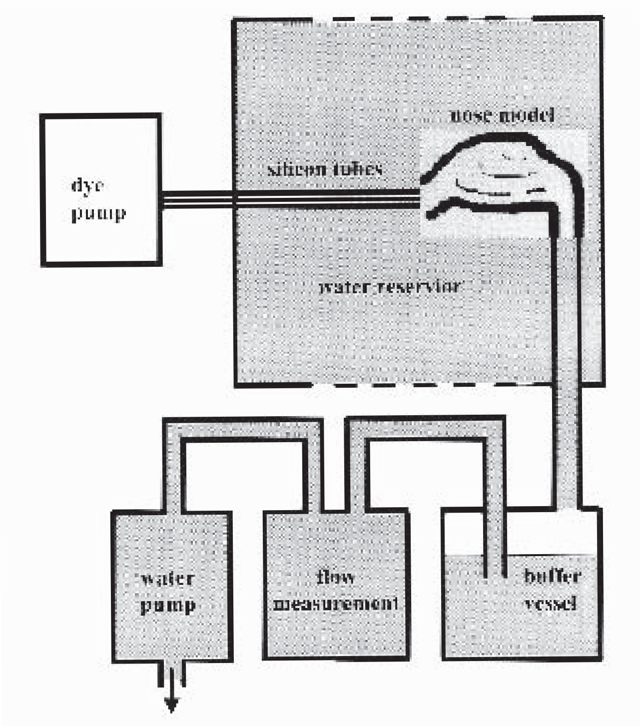

Figure 1. Schematic illustration of the experimental set up for fluid dynamics experiments.

We evaluated stream lines, flow distribution and turbulence behavior. Under laminar flow conditions (parallel flow of water and dye particles) clear margins of the stream lines are found. Turbulent flow behavior is characterized by sideways motion of particles. In this case water and dye become mingled. The flow patterns were judged by eye and recorded on video.

RESULTS

1. Inspiration

Vestibulum

In the vestibulum we observed a redirection of air flow (Figure 2). The air coming from anterior, inferior and lateral was deflected towards the area of the turbinates. This change in direction for the central stream line in the sagittal plane was approximately 30-40°. Up to a velocity of 800 ml/s flow behavior within the vestibulum appeared laminar.

Isthmus

As demonstrated in Figure 3, the isthmus nasi, or as Bachmann (1968, 1972) called it: the functional internal ostium, forced the stream lines to diverge. In inspiratory direction, the isthmus has a concavely curved shape. In order to find out how a curved shape influences flow, we compared flow in Mink's boxes with straight and with curved inflow openings. In the case of a straight opening, parallel stream lines through the box were found (Figure 4A). Stream lines through the box with a curved opening – similar to the nose – diverge (Figure 4B).

Anterior cavum

In the anterior cavum, i.e. in the zone between isthmus nasi and head of the middle turbinate we observed a transition from laminar flow to turbulent flow depending on the shape of the anterior cavum and on flow velocity.
The area of the anterior cavum is characterized by an increase in cross-sectional area. The influence of the degree of increase in cross-sectional area on the occurrence of turbulence was investigated with the help of Mink's boxes (Figure 5). At a high amount of increase in cross-sectional area (Figure 5A) turbulent flow behavior is seen close behind the inflow opening, whereas for less increase in cross-sectional area (Figure 5B) turbulent flow occurs much further away from the inflow opening. For a given opening angle, the point of onset of turbulence was observed to shift from further away from the inflow opening at low velocities towards the inflow opening at high velocities (data not shown).
When flow velocity in nasal models exceeded 20 ml/s a transition from laminar to turbulent flow behavior (Figure 6) and a decrease in flow velocity was found.
The occurrence of turbulence depended thus on the increase of cross-sectional area and on flow velocity.

Area of turbinates

At very low flow (approximately up to 15 ml/s) laminar flow was observed (Figure 6A). The stream lines stayed narrowly together, preventing ventilation of the olfactory region and the inferior nasal duct. With increasing velocity, turbulence increased. At a velocity of about 300 ml/s, equal distribution and completely turbulent flow was seen across the entire area of the turbinates (Figure 6B)

The influence of the *posterior cavum, choanae* and *epipharynx* on flow behavior were impossible to assess with this experimental set up. because dye and water once mingled do not separate when transition from turbulent to laminar flow happens.

DISCUSSION

On the basis of the results presented here it appears possible, to allocate various segments of the nose to structural elements, the influence of which on flow dynamics is known from fluid mechanics. Bachmann's suggestions (Bachmann, 1982) can thus be extended and specified as illustrated in Figure 7.

The *vestibulum* is shaped like and acts as a bend. Air flowing into the nose from anterior, inferior and lateral is redirected towards the area of the turbinates.
The cross-sectional area of the vestibulum decreases from the external towards the internal ostium, thus representing a nozzle. This appears to be of importance for the next structures, the air has to run through. With the help of this nozzle, laminar flow is stabilized resulting in laminar flow through the tight isthmus even at high velocities.

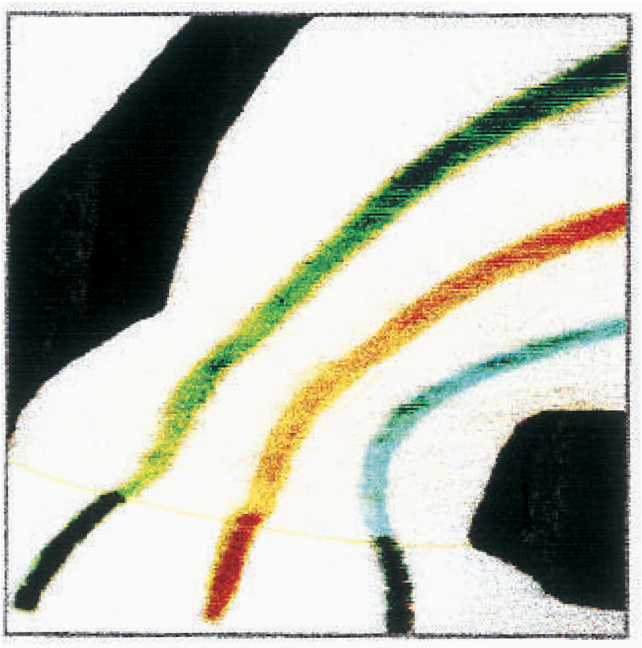

Figure 2. Flow through a nasal model. The vestibulum acts as a bend, redirecting air flow.

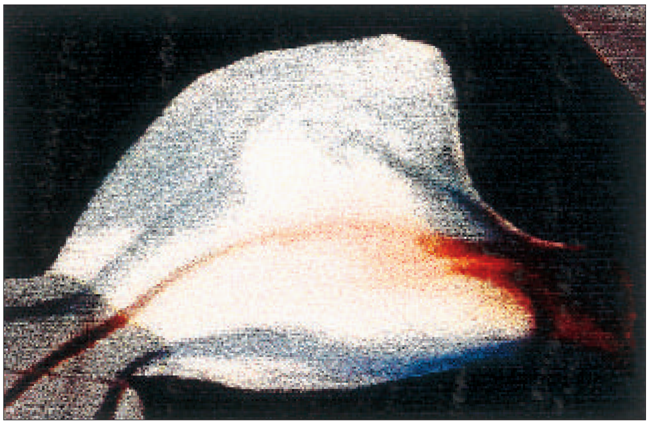

Figure 3. Flow in a nasal model without vestibulum. Stream lines diverge after running through the isthmus.

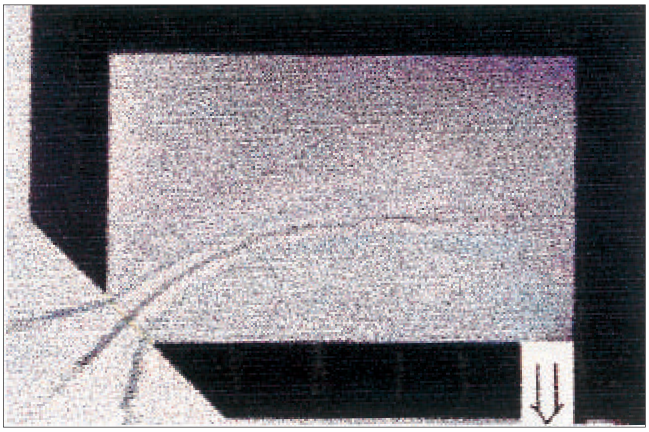

Figure 4A. Flow in a Mink's box with a straight inflow opening. Stream lines stay parallel.

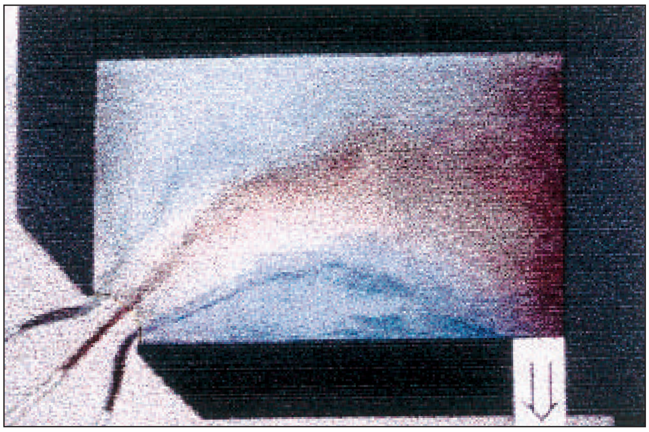

Figure 4B. Flow in a Mink's box with a concavely curved opening. Stream lines diverge.

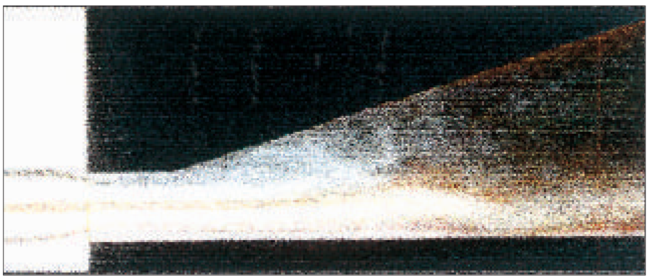

Figure 5A. Flow in a diffuser with a large increase in cross-sectional area. Onset of turbulence at the beginning of the diffuser.

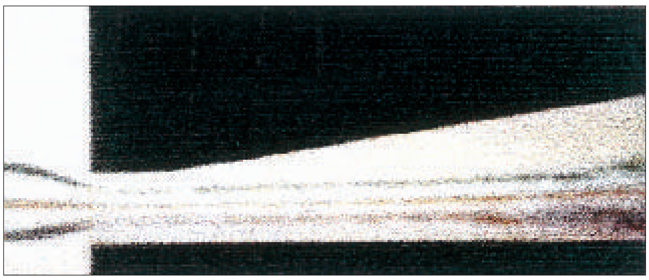

Figure 5B. Flow in a diffuser with a small increase of cross-sectional area. Onset of turbulence at the end of the diffuser.

Being the narrowest segment of the nose, the isthmus represents the highest flow resistance. Therefore, laminar flow throughout this segment is of enormous importance, for turbulent flow through the isthmus would cause an increase of flow resistance.

The opening between vestibulum and anterior cavum – *the isthmus nasi* – exhibits a curved shape (Bachmann, 1968 and 1972). The results support the facts known from fluid mechanics that the shape of an opening influences the course of stream lines. The concavely shaped isthmus causes streamlines to diverge similar to the effect of a concave optical lens on light. The specific shape of the isthmus nasi thus supports a homogenous distribution of flow across the area of turbinates.

The *anterior cavum* is characterized by an increase in cross-sectional area. In fluid dynamics, structures exhibiting an increase in cross-sectional area are known as diffusers. It is also known that in a diffuser, turbulence increases and velocity decreases. Due to a general increase in sideward movement particles flowing near to the side of the diffuser move sideways towards the center of the stream (detachment) while particles from the center move towards the side. The extent of turbulence and the amount of decrease in flow velocity depend on the increase in cross-sectional area of the diffuser.
The degree of turbulence and the amount of decrease in flow velocity seem to be regulated by congestion and decongestion of erectile tissues of the head of the inferior turbinate and the nasal septum. Occurrence of turbulence and decrease in flow velocity guarantee sufficient contact of air and mucosa and thus they are a crucial prerequisite for adequate respiratory function of the nose.

In inspiratory direction, the *vestibulum, isthmus and anterior cavum* form the inflow tract, the function of which can best be described as 1) directing the air flow towards the area of turbinates, 2) dispersing it across the entire cross-sectional area and 3) causing turbulence and decrease in flow velocity.

The *area of turbinates* exhibits a large mucosal surface and represents the actual functional area of the nose. From an aerodynamic point of view it can be described as slit-like space which facilitates contact of air and mucosa due to its small width.

In inspiratory direction, the *posterior cavum, choanae and epipharynx* represent the outflow tract. Although the experimental setup is not suitable for directly investigating the influence of the of these elements, because a comparison of the outflow tract with known structural elements and their influence on flow behavior leads to the following conclusions:
In the region of the *posterior cavum* cross-sectional area decreases. It can therefore be considered a nozzle. The degree of turbulence and thus resistance are decreased and air can proceed towards the lower airways in a largely laminar fashion.

The *choanae* resemble convexly curved openings when seen during inspiration causing the stream lines to converge. This seems to be of importance for the pharynx and the lower airways, the cross-sectional areas of which are smaller then the choanae.
The *epipharynx* is shaped like and acts as a bend, redirecting airflow towards the lower respiratory tract.

2. Expiration
During expiration, the anterior cavum becomes a nozzle, reducing turbulence and thus decreasing resistance within the isthmus. The isthmus now resembles a convexly curved opening causing the streamlines to converge into a narrow stream which leaves the nose forward, downward and sideways after its direction changes in the vestibulum.
In a comparable way the structures posterior to the functional area turn into an inflow tract during expiration. The air coming from the lower airways undergo a change of direction within the epipharynx (bend). An even distribution of expired air across the entire functional region as well as turbulence are again necessary for the contact of air and mucosa. This is guaranteed by the choane causing the streamlines to diverge due to its concave shape. The posterior cavum generates the needed turbulence due to the increase in cross-sectional area.
Adjacent to either side of the functional region of the nose a diffuser, a curved opening and a bend are found. Due to the cyclic change of direction of air flow during respiration the inflow tract turns into an outflow tract and vice versa.

CONCLUSION
In summary the following processes occur during inspiration and expiration:
* change of direction
* diverging of streamlines
* occurrence of turbulence and decrease in flow velocity
* contact of streaming particles with the mucosa
* decrease in turbulence and in flow velocity
* converging of streamlines
* change of direction

These processes are determined by the specific structural elements illustrated in Figure 7.

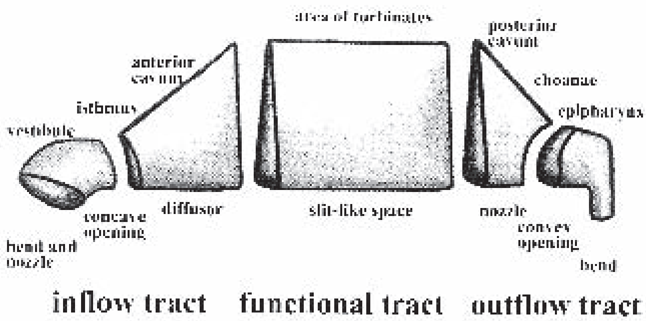

Figure 7. Structural elements of the nose in inspiratory direction.

Figure 6A. Flow in a nasal model at a velocity of 15 ml/s. Parallel stream lines indicate laminar flow.

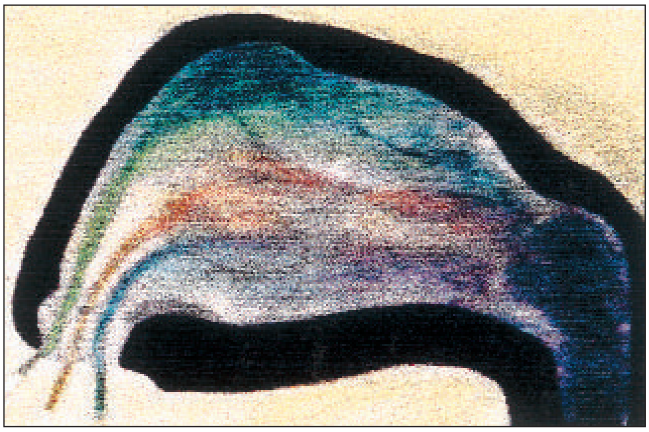

Figure 6B. Flow in a nasal model at a velocity of 300 ml/s. Onset of turbulence in the anterior cavum is visualized by the mingling of dye particles and water.

This systematic arrangement appears ingenious, for it provides the necessary prerequisites for sufficient contact of air and mucosa, which is essential for inspiratory release of energy and moisture to the air and for regeneration of thermal energy and fluid during expiration and thus for adequate nasal respiratory function.

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