EXPERIMENTAL STUDY OF VELOCITY FIELDS IN A MODEL OF HUMAN NASAL CAVITY BY DPIV

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ABSTRACT

The basic functions of the nose are the humidifying and warming of inspired air, filtering of air-born particles, and olfaction. Airflow patterns in the nasal cavity affect the performance of these functions. Velocity fields of human nasal cavity were investigated using DPIV (Digital Particle Image Velocimetry) in the present paper. A three times scaled-up half-nasal model of a human nasal cavity was constructed for the investigation of nasal flow patterns. To overcome the difficulties concerning DPIV for the study of flow patterns within the human nasal cavity in the air flow with physiological conditions, liquid was used instead of air. In this study tetrahydronaphtalene was chosen as a carrier medium in order to match the refractive index of working fluid to that of the solid transparent model for DPIV measurements. Steady flow rate equivalent to still breathing through one side of the real human nasal cavity was investigated here.

1. INTRODUCTION

The nasal cavity plays an important role as the main passage for air flow between the atmosphere and the lung airways in the respiratory systems. The basic functions of the nose are the humidifying and warming of inspired air, filtering of air-born particles, and maintenance of an airway resistance appropriate for physiological needs. The performance of these functions is influenced strongly by the airflow patterns in the nasal cavity. Experimental investigations of velocity fields within the nasal cavity are strongly required for improved understanding of the nasal airway transport processes.

Studies of the nasal air patterns have been conducted for many years. The early studies of nasal airflow patterns were involved in vivo observations of the distribution of air-born powder. However, the complex three dimensional geometry and small size of the nasal cavity has prevented detailed in vivo observations of airflow patterns. Therefore several studies have been performed in vitro model made from nasal casts to investigate better the internal flow patterns. Masing (1967) investigated the course of flow in the nose model using dye trails and observed that the flow patterns in the nose model depend on the location where the dye is released. The first quantitative study of airflow patterns in a nasal model was carried out by Swift & Proctor (1977). The velocity field was measured with a pitot tube. Giradin et al. (1983) measured the velocity field in a model of human nasal fossa at five cross sections by Laser Doppler Velocimetry (LDV). A continuous flow rate of 0.166 l/s was selected for the experiment. Time averaged velocity profiles obtained by LDV showed that airflow was streamed by the turbinates with lower peak velocity, velocity was higher near the septum and flow was usually higher in the lower half of the fossa. Hornung et al. (1987) constructed a nasal model that was anatomically correct. Airflow patterns in this model were investigated by using xenon 133 gas to image the course taken by air. The results confirmed those of Masing

(1967) and Stuiver (1958) who used water as the carrier medium. Because of the small size of the model, it was difficult to visualize the detailed flow patterns of the nasal cavity. Therefore, Scherer et al. (1989) and Hahn et al. (1993) constructed an anatomically accurate, 20 times enlarged scale model of a human nasal cavity from computerized axial tomography scans. Detailed velocity profiles for the flow through model and turbulent intensity were measured with a hot-wire anemometer. The results showed that 50 % of inspiratory flow passes through the combined middle and inferior airways and 14 % of the flow passes through the olfactory region regardless of flow rates. They showed that the air flow in the nasal cavity appears mostly turbulent at high and medium flow rate in the breathing cycle while the flow is laminar for the lowest flow rate.

In this study, we applied DPIV for the study of the air flow pattern in a model of the human nose. In contrast to earlier studies using hot wire anemometry or LDV, DPIV offers to obtain the instantaneous flow field within selected planes in the model which first provides detailed information of the flow structure but also makes experimental work much more practicable in such complex geometries.

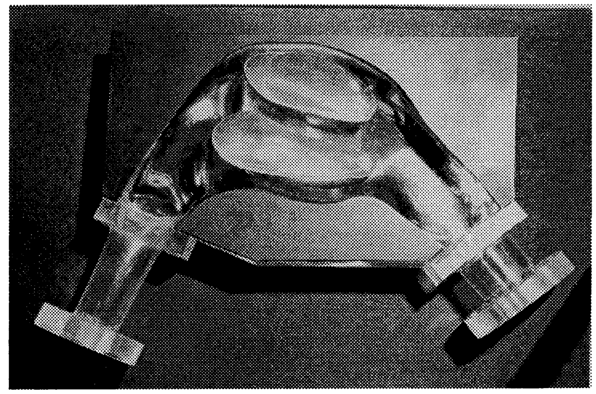

Fig. 1. 3:1 scaled up model of the human nose

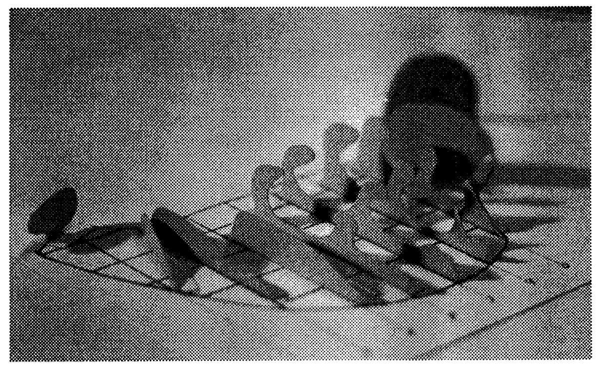

Fig. 2. Carton model of the nasal cavity

2. EXPERIMENTAL METHOD

Owing to the small size and complex geometry of the human nasal cavity, a 3:1 scaled up anatomically correct model of the human nasal cavity (Fig. 1) was used for the study of the flow patterns through a half nasal model using DPIV. The model with inferior and middle turbinates was constructed from geometry data representing the human nasal cavity by Masing (1967). A model made of carton (Fig .2) with sections from the nostril to the nasopharynx served as basis for the design of the model, Opitz et al (1997).

To overcome the difficulties concerning DPIV (Digital Particle Image Velocimetry) in investigating flow patterns through the human nasal cavity in air medium with physiological conditions, the transparent model that was made of epoxy-based casting resin was set in a water channel. This reduces, according to the similarity laws, the time scales such that video-based DPIV is applicable for maximum velocities in the model of order of 10 cm/s. Video-based DPIV also enables to resolve the temporal evolution of the flow during the breathing cycle.

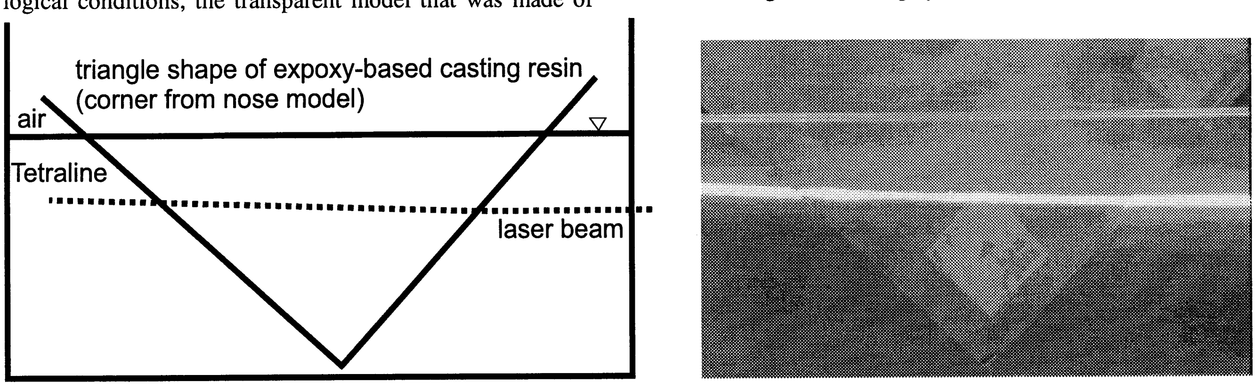

Fig. 3. Refractive index matching: the laser beam passes approximately as a straight line through a transparent container with tetraline and the model inside

A difficulty common to the optical diagnostic techniques is the refraction of light passing through liquid-solid or gas-solid interfaces at the model, Budwig (1994) . It needs to match the refractive index of the working fluid to that of the solid transparent model for DPIV measurements. In this study 1,2,3,4-tetrahydronaphtalene (tetraline) was used as a carrier medium. Its viscosity is twice that of water while its density is comparable so that the conditions of flow rate are not much different from using water. This liquid matches the refractive index of epoxy-based casting resin, but calls for particularly careful selection of acrylic and rubber materials to avoid chemical attack which leads to formation of stress crack, crazing and deformation. Fig. 3 shows a refractive index matching between the model and tetraline. One can see that the laser beam penetrates approximately as a straight line from tetraline into the model and out, which shows the good index matching. In spite of the nearly perfect index matching, the problem of total reflection appeared where the beam angle of incidence was high (flat to the surface). This occurs mainly in the nostril region which is not the focus of our study. Only few velocity vectors could be obtained in these regions.

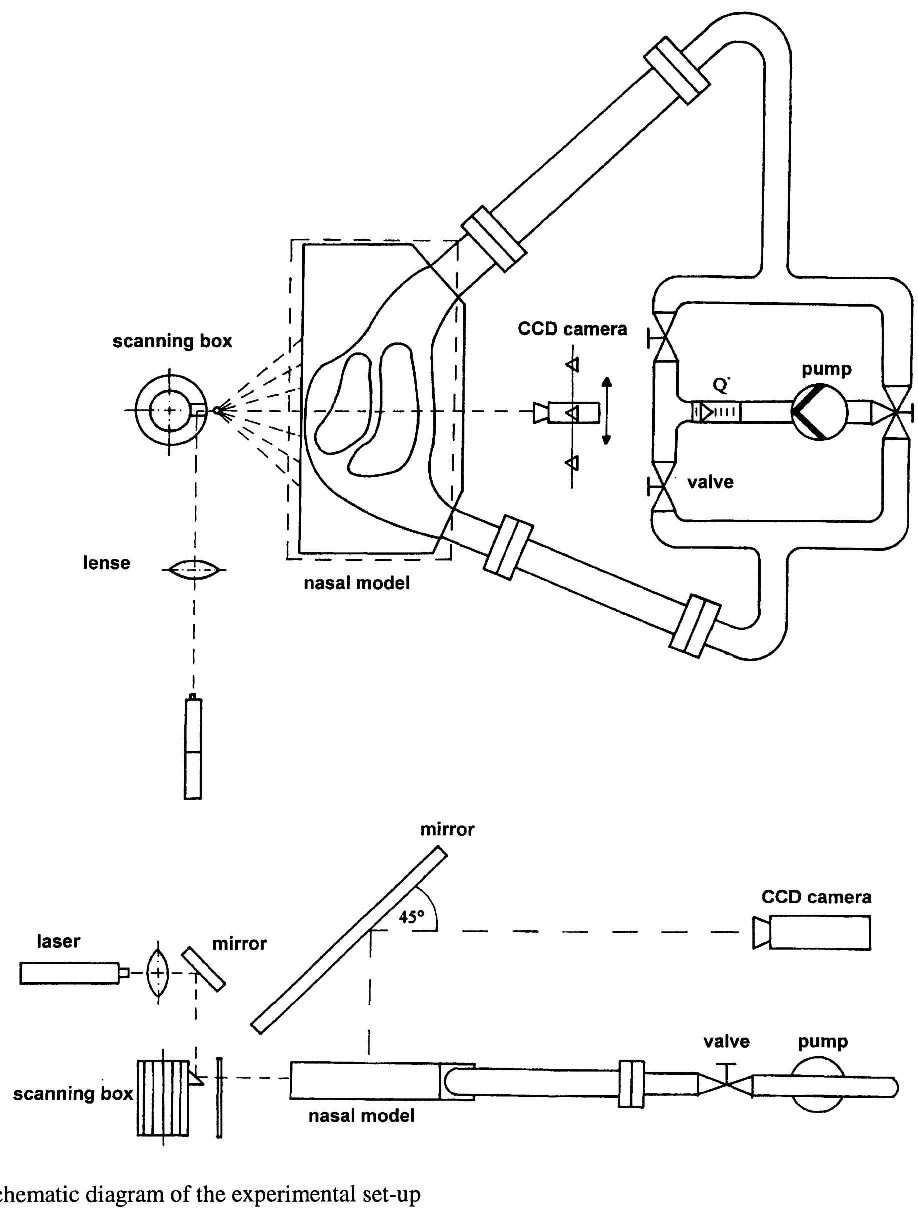

Fig. 4. Schematic diagram of the experimental set-up

Fig. 4 shows the schematic diagram of the experimental set-up for the investigation of flow patterns in the nasal cavity using DPIV. This consists of the 3:1 scaled-up half model of the human nasal cavity, a pump, PVC tubes, a light-sheet scanning box and the recording components. The schematic diagram of the nasal model is shown in Fig. 5. Two long PVC pipes with a diameters of D_1 = 3.6 cm and D_2 = 4.5 cm were connected to the nostril and the nasopharynx. The cross-sectional areas for one half of the nasal cavity were A_1 = 10.18 cm^2 at the nostril and A_2 = 16.62 cm^2 at the nasopharynx. Expiration and inspiration flow were first studied under steady flow conditions at a design flow rate of 2.5 l/min corresponding to a Reynolds number of 508 at the nasopharynx and 648 at the nostril. These values represent approximately the nasal flow at still breathing for an adult human according to the similarity laws.

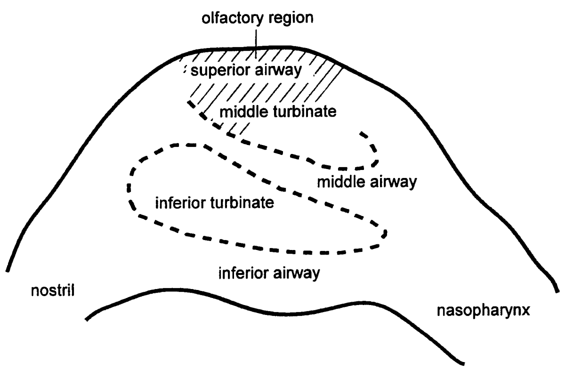

Fig. 5. Schematic diagram of the nasal model

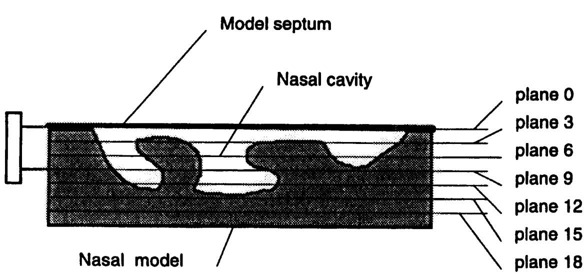

Fig. 6. Positions of the light sheet planes

A CCD-video camera connected to a S-VHS recorder observed the flow at a frame rate of 25 Hz in interlaced mode. After frame-by-frame digitization of the video tapes, the images (768x512 pixel format) were separated into their two fields of which missing odd and even horizontal lines were interpolated. Due to the relative low resolution, one video frame could not include the whole field image of the model with a sufficient resolution for DPIV at the given conditions. For this reason, images were recorded separately at 5 sections of the nasal cavity model. After the evaluation of the recorded images, the resulting velocity fields were joined together. Chronological DPIV recordings were taken in 18 successive light sheet planes parallel to the top plate of the nasal cavity model, see Fig. 6. The distance between adjacent planes was 2 mm.

3. RESULTS

Fig. 7 shows the velocity field (only the in-plane components of the vectors) during inspiration in the 3rd plane parallel to the top plate of the half nasal model which is about 16 % of the total depth of the model. The problem of total reflection appeared especially in the region of nostril. The irregular pattern of the 2-D velocity field in the plane demonstrates the strong three-dimensional nature of the flow especially in front of the turbinates caused by the complex three-dimensional geometry of the nasal cavity. During inspiration the flow is divided in the turbinate area into 3 main streams and unifies again in the nasopharynx. Along the leading edge of the middle turbinate the flow is accelerated into the olfactory region. The flow through the nostril streams mainly through the middle and superior airways. Hahn et al (1993) observed that about 14 % of the inspiratory flow streamed through the olfactory region which is the superior airway. A separation region is seen at the wall which is located in front of the middle turbinate. The flow to

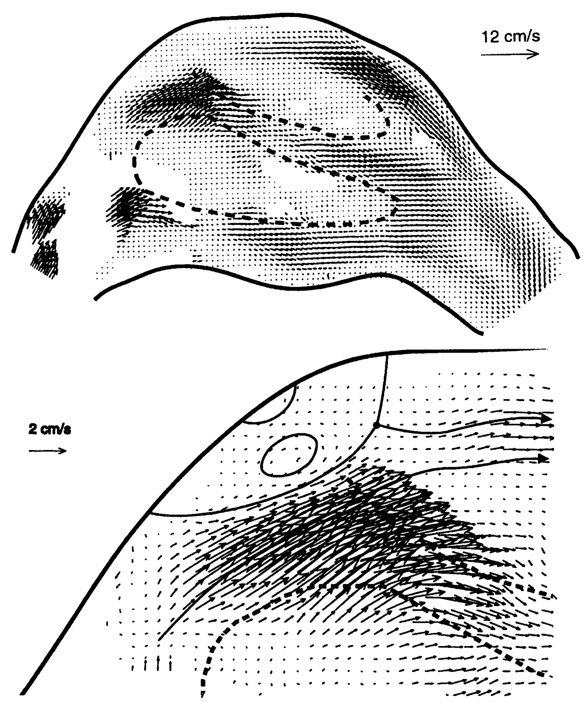

Fig. 7. 2-D velocity field in the plane 3 during inspiration (top: total view, bottom: close-up view)

the olfactory region leads through a narrow passage between the separation and the middle turbinate for which it is accelerated locally. Farther downstream behind the separation the velocity is reduced close to the upper wall in comparison to the mean flow in the superior airway. Hence, the fluid residence time in the olfactory region is longer than in the other regions.

An example of the expiration flow in the same plane of the model is given in Fig. 8. The most part of the flow during the expiration passes through the inferior and middle airways. In front of the middle turbinate, the flow seems irregular and non-uniform which is due to strong three-dimensional structure of the flow in this region which was also observed by Giradin et al. (1983). The flow turns upwards in front of the middle turbinate by the change of the channel depth. For this reason, the in-plane velocity of the flow decreases suddenly before and over the leading edge of the middle turbinate. A stagnation point is induced which causes a separation of the flow coming from the nasopharynx. The sectional stream line pattern obtained from the in-plane velocity field are compared with qualitative flow visualization using dye trails in the same model in Fig. 9. Both of the flow patterns looks very similar, while the DPIV investigation enables to describe the detailed flow patterns by means of the velocity field which was not possible from the preceding dye visualization reported in Opitz (1994).

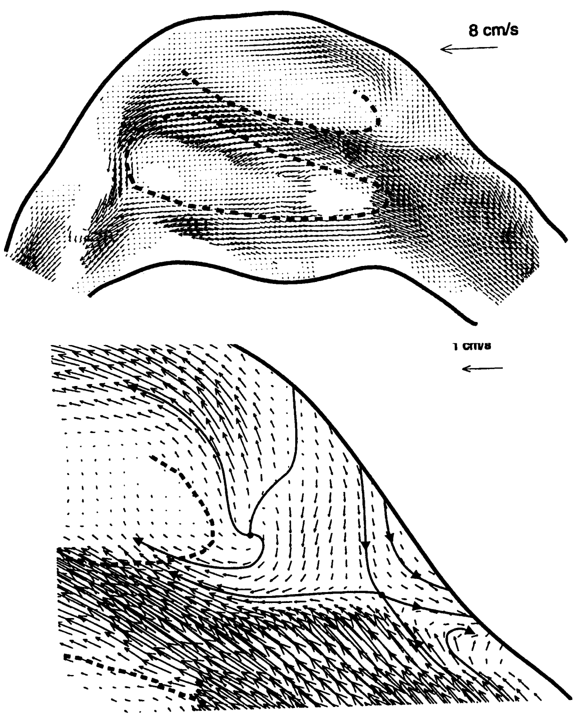

Fig. 8. 2-D velocity field in plane 3 during expiration (top: total view, bottom: close-up view)

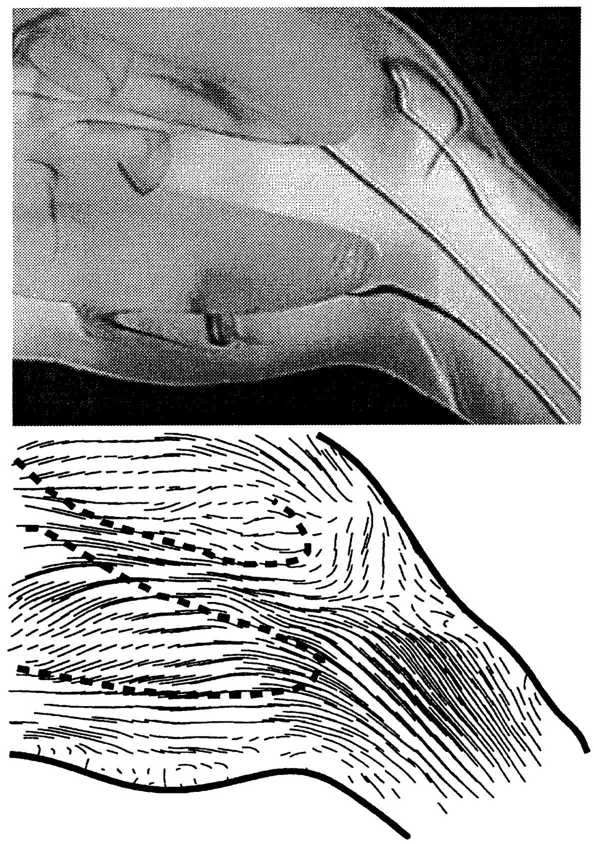

Fig. 9. Flow structure during expiration. top: flow visualization using dye filaments; bottom: sectional streamline pattern integrated from the velocity field in the 3rd plane

4. CONCLUSION

In the present paper flow patterns through a half nasal model were shown obtained from DPIV measurements in a three-times upscaled model of the nasal cavity. To overcome the difficulty of the DPIV measurement in an air medium of the nasal cavity and difficulty of index matching between the model and liquid, tetraline was used as a carrier medium. Tetraline has the problem of chemical attack but it matched nearly perfectly the refractive index of the model. The flow characteristics in the olfactory region and in the vicinity of the turbinate could be measured in detail within a set of parallel planes through the model. The successful application of DPIV to the model of nasal cavity using refractive index matching implies a wide range of other possible PIV application in the area of biofluid mechanics where complex geometry is under investigation.

Compared to LDV measurements and hot wire anemometry, the velocity field obtained by DPIV let recognize the flow pattern in a more global view in the nasal cavity. The general characteristics of the velocity fields are compatible with the results from [3], [7] but the whole field velocity results offer more detailed analysis of the vortical structures generated within the cavity, e.g. within the olfactory region or in the vicinity of the turbinates. One of the conclusions drawn from the DPIV experiments is, that the flow over the nasal turbinates strongly resembles the flow between turbine blades for which extensive studies already have been carried out. The reconstructed flow patterns in the nasal cavity show the typical wall-bounded horse-shoe vortices generated in front of the turbinates which interact with the walls. First indications could be found for an evolutionary optimized design of the turbinates to reduce the pressure loss in the curved nasal cavity.

In spite of the flow field information obtained by DPIV in the parallel planes of the model, the results demonstrate that it is still difficult to understand exactly the flow patterns only with 2-D velocity information due to the complex geometry. Future studies will therefore be carried out with an improved technique called Scanning Particle Image Velocimetry (Brücker 1996) and a high resolution video camera which will offer to obtain the three-dimensional flow field over the entire model.

5. REFERENCES

Masing, H., 1967: "Experimentelle Untersuchungen über den Strömungsverlauf im Nasenmodell", *Arch. Klein. Exp. Ohren-. Nasen- u. Kehlkopf-Heilk.*, 189, pp. 371-381.

Swift, D. L. and Proctor, D. F., 1977 : "Access of air to the respiratory tract". In *Respiratory defense mechanisms*, Brain, J. D., Proctor, D. F. and Reid, L. M. (Eds.), New York, Marcel Dekker.

Girardin, M., Bilgen, E. and Arbour, P., 1983 : "Experimental study of velocity fields in a human nasal fossa by laser anemometry", *Ann. Otol. Rhinol. Laryngol.*, 92, pp. 231-236.

Hornung, S. E., Leopold, D. A., Youngentob, S. L., Sheehe, P. R., et al., 1987 : "Air-flow patterns in a human nasal model", *Arch Otol. Head Neck Surg*, 113, pp. 169-171.

Stuiver, M., 1958 : "Biophysics of the sense of smell", thesis, Groningen, Netherlands.

Scherer, P. W., Hahn, I. and Mozell, M. M., 1989 : "The biophysics of nasal airflow", *Otolaryngol. Clin. N. Am.*, 22, pp. 265-278.

Hahn, I., Scherer, P. W. and Mozell, M. M. 1993 : "Velocity profiles measured for air-flow through a large-scale model of the human nasal cavity", *J. App. Physiol.*, 78, pp. 2273-2287.

Opitz, R., Limberg, W. 1997 : "Experimentelle Untersuchungen der Strömung in einem Nasenmodell", treatise from aerodynamic institute of RWTH Aachen, 32, pp. 120-129.

Budwig, R., 1994 : "Refractive index matching methods for liquid flow investigations", *Exp. In Fluids*, 17, pp. 350-355

Brücker, Ch., 1996: "3-D Scanning Particle-Image-Velocimetry (3-D SPIV) ". VKI Lecture Series "Particle-Image-Velocimetry", Von Karman Institute, Rhode-St-Genese, Begium