*Proc. Computer Aided Surgery around the Head*, Pro Business Verlag, pp. 173-176, 2007

# Understanding nasal airflow via CFD simulation and visualization

Stefan Zachow, Alexander Steinmann, Thomas Hildebrandt, Werner Heppt

**Our objective is to analyze and understand the physiology and patho-physiology of normal nasal breathing. To this end, airflow simulations based on computational fluid dynamics (CFD) are presented for a highly detailed anatomy of the upper respiratory tract from the external nose to the larynx, including frontal and maxillary sinuses, as well as the ethmoid. Complex flow phenomena are investigated with regard to individual anatomy and its variations. We are aiming to gain insight into the relationship between morphology and flow behaviour in order to provide general treatment proposals and to develop computer assisted planning tools for decision support in functional rhinosurgery.**

**Keywords:** computational fluid dynamics, CFD, functional rhinosurgery, nasal airflow

**Introduction.** A major requirement for normal nose breathing is an undisturbed passage through the nasal airways. In cases where this condition is not given due to any persistent obstruction or deformity, e.g. paranasal sinusitis, nasal polyps, or septal deviation, a surgical correction might be indicated. Very often too radical resection of turbinate mucosal tissue results in a so called 'empty nose syndrome' (ENS). [1] There is no standard, however, of how much turbinate tissue *has to* be removed to re-establish physiological breathing. Neither, it is known how much tissue *can* be removed before it causes other damage to the physiology of the nose, such as ENS. An in-depth knowledge of normal nose breathing, as well as an understanding of the relationship between morphology and physiology of the nose will be the foundation for an improved surgical rehabilitation.

**Material and Methods.** Our investigation is based on an anatomical model of the nasal airways, derived from a high resolution CT scan (Toshiba Aquilion 64) of a volunteer without obvious pathological symptoms (**Fig. 1**, left). Local administration of a decongestant (Xylometazoline) as well as a systemic application of Methylprednisolon was used to enhance the reconstruction of narrow airways. In addition to the CT scan, a series of active anterior rhino-manometry (AAR) measurements was taken on the same subject in a comparable mucous membrane swelling condition, gathering 2000 samples per measurement (RhinoLab, HR2, **Fig. 1**, right).

The geometric 3D reconstruction of anatomical structures from the CT slices was performed with the software AMIRA. [2] A volumetric Finite-Element (FE) mesh of inner airway structures was generated, as well as of the anterior inflow region. The facial skin serves as boundary surface to address individual inflow via the external nose (**Fig. 2**, left and **Fig. 3**). An unstructured FE mesh of the entire computational domain with locally controlled resolution and mixed element types (tetrahedra, prisms) of suitable element quality was finally exported in CGNS format for CFD simulations with ANSYS CFX. [3]

[1] http://emptynosesyndrome.org
[2] http://amira.zib.de, http://www.mc.com/amira
[3] http://www.ansys.com/cfx

*Proc. Computer Aided Surgery around the Head*, Pro Business Verlag, pp. 173-176, 2007

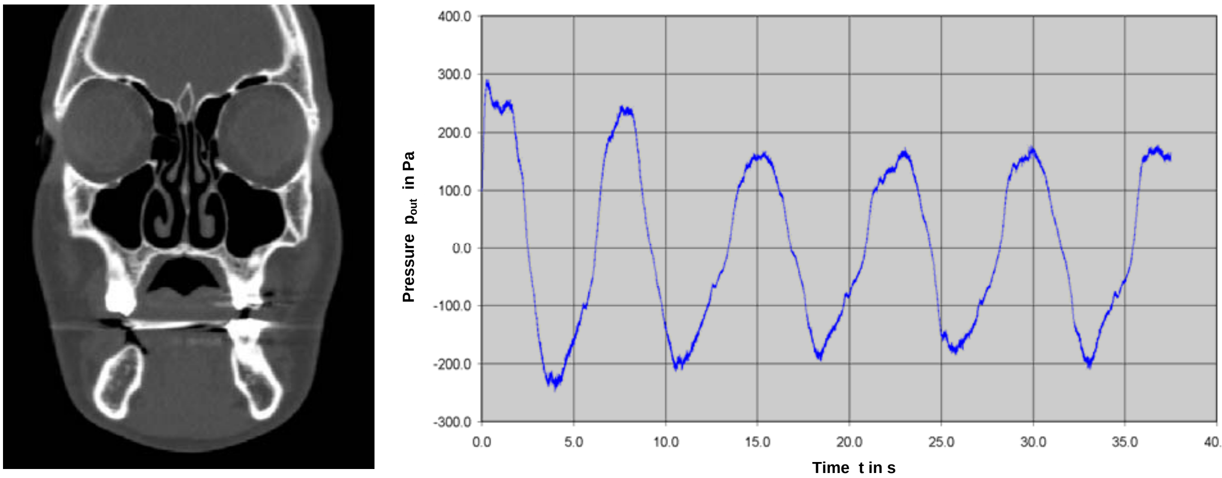


**Figure 1.** left) reformatted coronal slice of an axial CT, right) AAR measurement

**Results.** In a first step, a grid independence study has been conducted, comparing the computed volume flow with measured values for different mesh resolutions. A mesh resolution of about 2.5 million elements and above, did not produce a significant change of the total flow rate anymore (≤ 1%). An apparent left-right difference could also be confirmed with the simulation. After several steady state calculations with geometric modifications **[1]**, a transient flow representing a total of 5 breathing cycles within approx. 35 seconds (225 time steps) was simulated. The mucosa wall is assumed to be smooth considering flow involving friction. Air is modeled as an isothermal and incompressible medium with a density of 1.185 kg/m$^3$ and a dynamic viscosity of 1.831 e$^{-5}$ kg/(m s) at a temperature of 25° C and ambient pressure of 101 325 Pascal. A pressure difference of up to 250 Pascal between inlet and outlet (lung) as a function of time has been applied as boundary condition. These values were taken from the AAR measurements, as shown in **Fig. 1**.

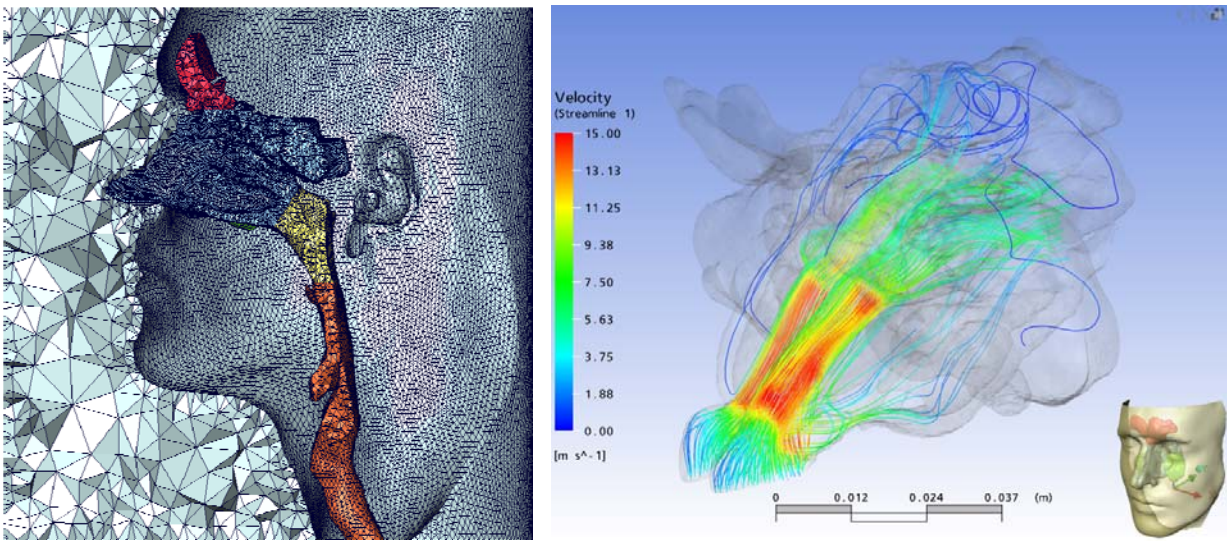


**Figure 2.** left) FE mesh of the respiratory system including inflow region, right) Streamlines coloured by velocity for nasal inhalation (ventilation of frontal and maxillary sinuses)

*Proc. Computer Aided Surgery around the Head*, Pro Business Verlag, pp. 173-176, 2007

The results of the airflow simulations, such as velocity components, pressure, temperature, turbulence quantities, etc., are currently evaluated. Visual data analysis methods, like color coding, contour plots, iso-surfaces, vector visualization, line integral convolution (LIC), streamlines (color coded, illuminated and/or animated, as shown with **Fig. 2** and **3**), and particle tracing with flow animations, that have been developed over time, allow for a vivid visualization and intuitive exploration of CFD simulation results **[2]**.

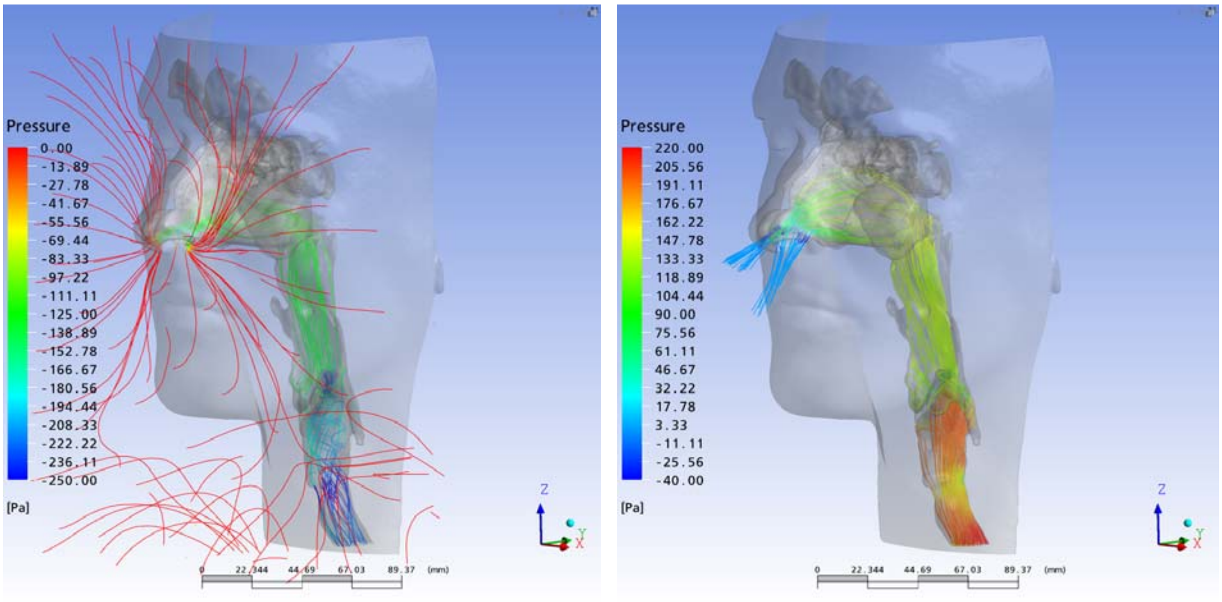


**Figure 3.** Streamlines coloured by pressure for inhalation (left) and exhalation (right)

**Conclusions and Future Work.** We did establish a processing pipeline that enables us to study very complex airflow phenomena. In further investigations the humidification of nasal airflow will be considered as a multi-component flow with an additional transport equation for water vapor. On that account the humidity charge of the nasal mucosa as well as the humidity transfer between mucosa and air will be modeled and simulated. Another objective is to study the administration of drugs via the respiratory system, which can be regarded as a multi-phase flow consisting of liquid droplets (disperse distributed particle flow) in a continuous air stream. Furthermore, heat transfer mechanisms will be investigated within the near future. Fluid-structure coupling, i.e. flow induced deformations up to physiologically induced swelling states of the mucosa are mid-term perspectives, and the coupling of the upper and lower respiratory system (lung) offers computationally demanding possibilities of long-time research, e.g. the investigation of aerosol distribution or the study of functional impairments, like for instance asthma.

For a better understanding of the relationship between nose morphology and respiration the effect of changes of the external nose is currently investigated. Using an advanced biomechanical tissue model, the shape of the external nose can be varied in a relistic manner, i.e. increasing or decreasing the nasolabial angle or the cross-section of the nasal valve. Such deformities may disturb the inspiratory inflow resulting in an increased resistance, an impaired distribution of the airstream, or a pathological turbulence behavior. An interactive alteration of the geometry of the nasal airways, like the deformation or perforation of the nasal septum, or even tissue resction, like a turbinectomy, in combination with CFD analysis is a basis for a sophisticated planning tool in virtual rhinosurgery. The conclusions that can be drawn might have an important impact on future surgical and conservative therapeutic concepts, thus driving clinical research.

## References

[1] Zachow S., Steinmann A., Hildebrandt T., Weber R., Heppt W.: "CFD simulation of nasal airflow: Towards treatment planning for functional rhinosurgery", Int. J. of Computer Assisted Radiology and Surgery, Springer, pp. 165-167 (2006)

[2] Stalling D, M Westerhoff, HC Hege et al.: Amira: A Highly Interactive System for Visual Data Analysis. (amira.zib.de) In: Hansen, CD and CR Johnson (eds.): The Visualization Handbook. Elsevier (2005), chapter 38, pp. 749-767 (2005)