Strömungsmesstechnische Untersuchungen für CFD-basierte Vorhersagetools der Strömungsverhältnisse in den Nasennebenhöhlen

Flow measurement investigations of CFD based prediction tools for airflow in the paranasal sinus

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Abstract

In this study the air flow behavior within the breathing process (inhalation) by means of Finite Volume Method (FVM) and Lattice Boltzmann Method (LB) is carried out. Validation of both simulations is performed using LDA (Laser Doppler Anemometry) measurements. To this end, two relevant velocity components are ascertained. However, within the scope of both simulation methods and the realized measurement show qualitatively and quantitatively similar results. Along one representative evaluation line one velocity component of the numerical simulation differs from the corresponding measured values less than 15%. These preliminary results should create the basis for a future simplification of the simulation and measurement regarding the complex system of paranasal sinuses, in order to create a tool for reliable surgery outcome.

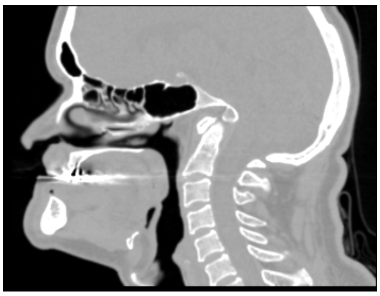
Introduction

Breathing in terms of air flow and air turbulences is a comparatively complex procedure within the nasal cavity, the sinuses and the nasopharynx, which are inherently complex spatial structures that may be caused by anatomical deformations and pathologies. Diagnostic identification concerning the necessity and potential success rate of nose surgeries is so far done either by rhinomanometry or endoscopy. Unfortunately both methods are rather uncomfortable for the patient. So there is the need to develop a reliable prediction tool for nose surgeries. Lattice Boltzmann (LB) [1] is mainly used to simulate the flow within respiratory ducts. However, the reliability of simulations can only be confirmed by in-situ measured data or a comparison with established simulation methods. Therefore, the conventional Finite Volume Method (FVM) [2] within respiratory ducts is compared with LB. Furthermore, LDA measurements validate the simulation results. For reasons of simplification the simulations and measurements are initially carried out on a simplified nose model. However, the investigated shape is derived from the complex geometry. In order to get information on the paranasal sinuses a CT (Computer Tomography) dataset is used and the surface of the respective anatomical situation is extracted and simplified. A constriction which can be found near the entrance at coronal position at the frontal sinus is implemented in the simplified nasal phantom (Fig 1. Detail A). This shape is reduced to a cuboid structure. The flow boundaries for the simulations as well as for the measurements are taken from a standard diagnostic rhinomanometry. However, the sinusoidal breathing process is rather difficult to acquire within an LDA measurement process. Therefore, maximum flow rate of 800 ml/s which corresponds to the maximum flow rate during the breath is taken into account for the simulations and the measurement.

Anatomy derived boundary conditions for the simplified nose model

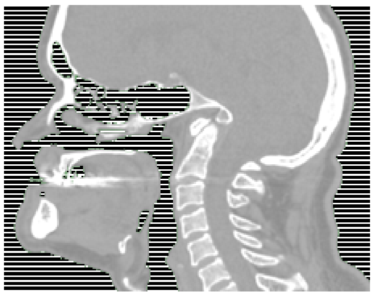
In order to create a simplified nose model, basic information about the anatomical structure has to be available. Since the complex geometry is also used for following investigations of this project, geometrical information can be taken from a segmented CT dataset. The used CT machine features a resolution of 0.4 x 0.4 x 0.8 mm^3. However, in this case the plane resolution is higher compared to the cranial-caudal direction. The information is an array of voxels (i. e. small volume elements) that shows a grey value depending on the physical density of the object made up from these elements. The segmentation process is required to generate the desired 3D-geometry from the CT dataset. Fig. 1 (a-d) shows all process steps in chronological order. At the beginning there is a thresholding step in order to detect the desired region (air) of the human's head. (b). Due to different grey values it is possible to determine the difference between bone, soft tissues and cavities. Especially for the cavity it is necessary to find an entrance and exit which is limited by horizontal boundaries (c). Subsequently, the marching cubes algorithm (d) [3] allows creating a surface geometry which can be used at a later stage for measurements and simulations.

a



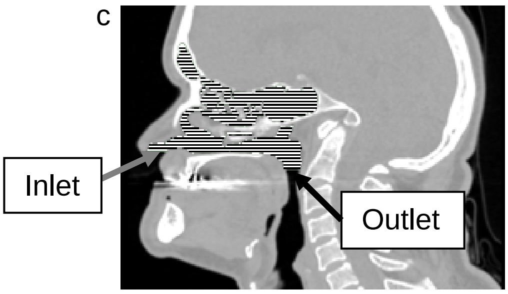
Saggital slice of CT Dataset: Color depicts density. Black: air, White: bone.

b



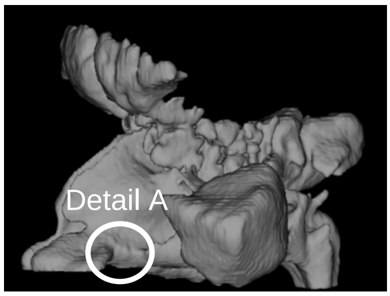
Thresholding to air: Voxels of grey value, which are smaller, than a dedicated value are selected.

c



Inlet and outlet boundary condition is defined with horizontal boundaries.

d



Marching Cubes Algorithm Outcome: 3D-surface of segmented volume. Detail A: constriction borrowed from human's nose.

Fig. 1: Segmentation from CT to STL.

This structure of the complex nasal geometry represents the basis for the creation of a simplified design. Basically it consists of two U-shaped canal structures with two inlets and one outlet. For the flow analysis the consideration of one of these canals is sufficient in this approach. Fig. 1 - Detail A depicts the constriction which is taken into account and can be found in an indentation - Fig. 2 is showing the simplified model.

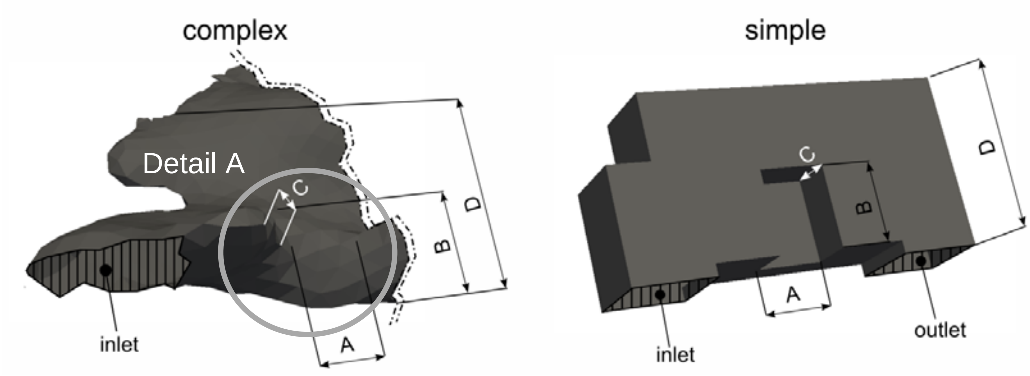


Fig. 2: Model simplification. Left: Complex nasal canal out of STL (segmentation). Right: Simplified nasal model.

The necessity of simplification has impact for optical accessibility for the LDA measurement system. In order to achieve adequate measurement quality, the reflections need be reduced to a minimum. Therefore, the top and bottom boundary are made of glass, all side elements are cut out from polymethyl methacrylate (PMMA). The obstacle is created by a 3D-printer at a high resolution (14 µm voxel size). A fan generates an accurate air flow rate, which is provided by an additional hot wire flow meter (FIC) via a closed loop control system. Additionally, a difference pressure sensor (PI) continuously monitors the pressure drop within the model.

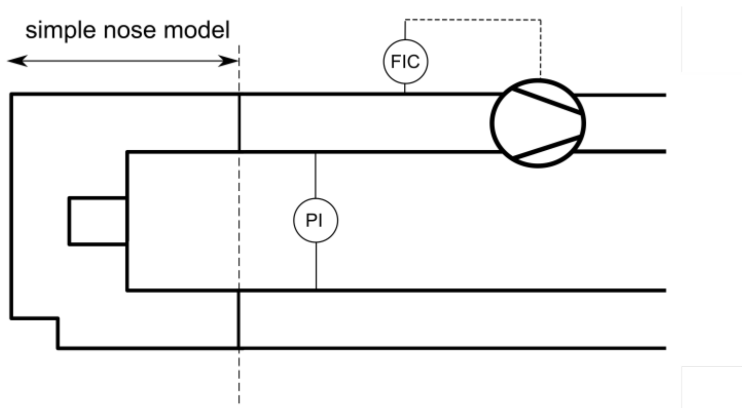


Fig. 3: Layout of the measurement setup.

The Reynolds number based on the hydraulic diameter (Re_D) within the outlet zone is approximately 3000. For comparison the critical Re for pipe flows is taken into account, which is about 2300. Thus, the flow is located in the transition region between laminar and turbulent flow behavior.

Simulation based on the FVM

For the analysis the software package Fluent® is used to predict the flow in the simplified model. Therefore the physical model must be reduced to a mathematical representation. For the representation of turbulences in the numerical analysis the realizable k-epsilon model with enhanced wall treatment [2] is chosen. A fully distortion-free (skewness = 0) mesh allows fast convergence of every time step. However, the simulation with a time step size of 0.0001 s is chosen, enabling fast convergence of every time step. After 0.05 s a steady solution is achieved. The momentum and continuity equation are solved with second order accuracy in order to avoid the effects of numerical diffusion. The convergence criterion for all transport equation variables (velocity, continuity, k and epsilon) smaller than 1e-6 is accomplished for every single time step.

Simulation based on the LB

Lattice Boltzmann (LB) uses a totally different approach compared to conventional FVM. Instead of solving an integral formulation the Navier-Stokes equations, the discrete Boltzmann equation is solved by collision processes, i.e. the chosen Bhatnagar-Gross-Krook (BGK) [1] and propagation. For turbulence modelling Large Eddy Simulation (LES) [4] is used. Unfortunately, the computational effort of this alternative simulation technique is higher. This can be compensated with code parallelization. Therefore, the software package Sailfish CFD [4] is used, which enables the use of the Graphical Processing Unit (GPU). However, a major advantage is a stable and simple implementation for complex geometries.

Measurement setup

In Fig. 4 the basic measurement setup for CFD validation is depicted. The used LDA system is the "LDV probe fp50" with two servo motors. Therefore, the examination plane is chosen on the constriction. Since the used LDA system can temporally measure only one velocity component in plane, the measurement is done twice to get the plane velocity $\vec{U} = \vec{u} \cdot \vec{\imath} + \vec{v} \cdot \vec{\jmath}$, where $\vec{\imath}$ and $\vec{\jmath}$ are the unit vectors in the direction of x and y. The plane is discretized with a grid spacing of 1 mm, which is depicted as a grey surface in the figure. Furthermore, an extraction line EL (see Fig. 4) is introduced to evaluate and compare the velocity in a 2D graph, in order to get qualitative information of the flow. This EL is located with 5 mm offset (x-direction) from the constriction. Particles, which are needed as tracer for the LDA measurement, are generated by a seeding generator.

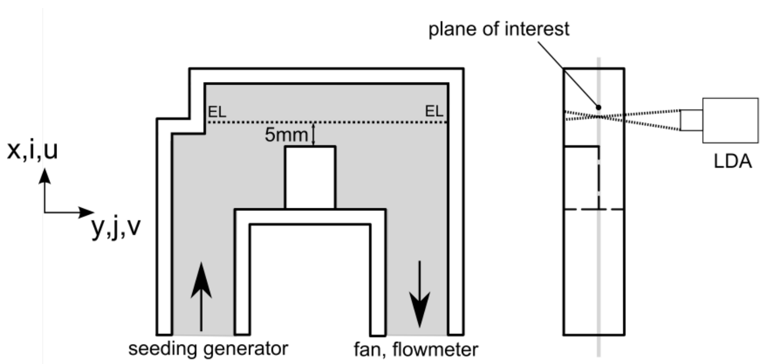


Fig. 4: Measurement setup. Left: Top view with the information of the measurement coordinate system. Right: LDA setup and information of plane position.

Qualitative comparison

Fig. 5 shows the simulated and measured results. A flow of this Reynolds number reveals transient behavior, which creates the need of further processing before the results can be compared. In LDA measurements the tracer particles are exposed by the fringe pattern and detected by a camera. Thus, the time step size is not constant. However, the used LDA software for post processing calculates the mean value for every measurement point. As well as the LDA measurement, LB is a transient process too. The time step size is set to 0.002 s, since the movement of turbulent structures is identifiable with this simulation time. Furthermore, the simulation end time is set to 10 s having enough data for a subsequent averaging. With this method it is possible to have nearly an equivalent procedure compared to LDA. Finally, the FVM with the turbulence model realizable k-epsilon (rke), achieves a steady solution after 0.05s. The reason for this short simulation time is that Reynolds Averaged Navier Stokes (RANS) model with rke is not able to indicate small-scale turbulent structures.

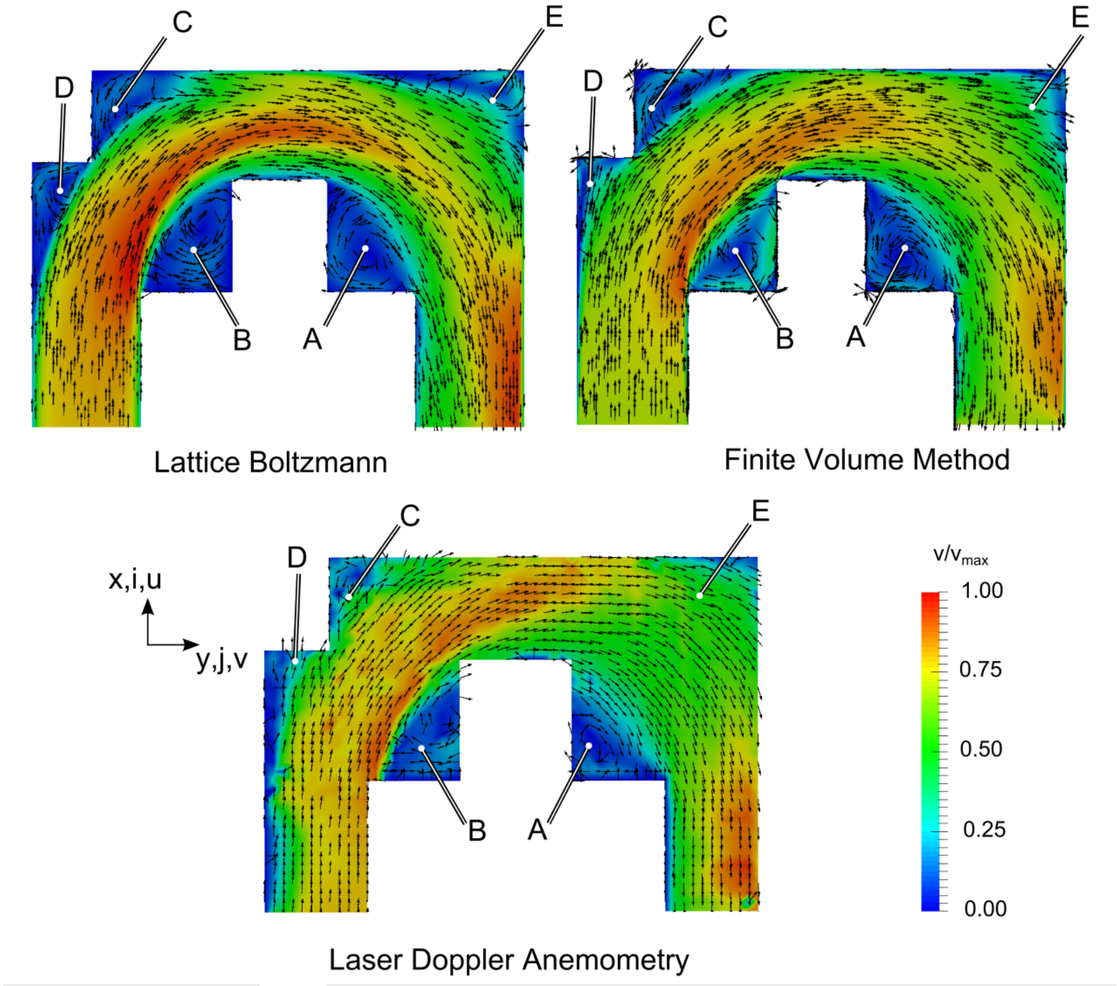


Fig. 5: Comparison of the plane velocity between LB, FVM and LDA. Markers A-E show plane vortices.

Fig. 5 depicts that the simulations and measurements have the same flow patterns. The magnitude of the vectors is encoded in the color-thermometer. All graphics show a contour plot of the normalized plane velocity $\vec{U} = \vec{u} \cdot \vec{i} + \vec{v} \cdot \vec{j}$. The vectors should give information on the flow direction, although, all vectors in the graphic have the same length. Additionally, there are markers from A-E positioned in the graph, which represents vortices within the flow field. All predicted vortices by the simulations have also been detected by the LDA measurement. Only the simulation technique FVM could not indicate vortex B. Since the flow is mainly two-dimensional the investigation of the third dimension is so far neglected.

Quantitative comparison

Additionally, in order to get qualitative information about the accuracy of the simulations compared to LDA measurement, the in-plane velocity of the y component is depicted within a 2D plot (Fig. 6). On the abscissa the position of the extraction line EL from outlet to inlet direction is shown.

Fig. 6: Comparison of the in-plane velocity in y-direction along the extraction line EL. The dots of the LDA result represent the real measured values. At the LDA and LB results a Gaussian distribution fitting with the histogram of two selected points is shown. The boundary lines of LB and LDA shows the standard error in a confidence level of 95%.

Since LB and LDA delivers transient information, all this data is used here for the validation. Due to the RANS model, FVM reaches a steady solution, although, it is a transient simulation too. However, at LDA and LB represents a so-called quasi-steady solution, since the turbulent effects create temporally slightly fluctuating velocity changes. The discrete LDA measurement points are interpolated with the Delauny triangulation [5]. For all measurement points a statistical uncertainty of 1% is achieved. In order to compare the transient effect the datasets are fitted by a Gaussian distribution [6]. The expected value μ and the standard deviation σ are calculated for two selected points along the extraction line. The higher the velocity fluctuation, the higher the degree of turbulence. For both, LB and LDA, the degree of turbulence increases with the distance to the inlet.

Discussion

Basically both simulation techniques and the LDA measurement show a good agreement. The flow regions near the walls are difficult to measure, since the laser orientation limits the detection of those regions. For this reason, these areas are neglected in the evaluation process. The LDA measurement helps to improve the quality of FVM and LBM, finding the right boundary conditions for the two different simulation techniques. Another important point is that FVM need a lot of preparatory work creating an adequate mesh, which is fortunately not necessary in LBM. This study has not the aim to optimize simulation times but to compare FVM, LBM with actual LDA based measurements in order to validate patient specific anatomy to create a predictive tool in paranasal surgery.

Outlook

With the experiences gathered at the simplified nose model, the next step is to apply the same simulation and measurement techniques (LB, LDA) based on CT patient specific anatomy and pathology. The validation of LB code by LDA measurements should allow predicting the success of a nasal surgery.

Literature

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