Die Verwendung einer LDA validierten Strömungssimulation zur Untersuchung eines Patienten mit Nasenscheidewandschiefstellung vor und nach einer Operation zur Verbesserung der Nasenatmung

The utilization of a LDA validated flow simulation to investigate the patients' flow through the nasal cavity with nasal septum deviation pre- and postoperatively

[1,2]M. Berger, [1,3]M. Pillei, [1]A. Mehrle, [4]W. Recheis, [5]F. Kral, [2]W. Freysinger and [1]M. Kraxner

[1]MCI, Department for Environmental, Process and Energy Engineering
Maximilianstraße 2, 6020 Innsbruck, AUSTRIA

[2]Medical University Innsbruck, Univ. Hospital of Oto- Rhino- Laryngology, 4D Visualization Laboratory,
Anichstraße 35, 6020 Innsbruck, AUSTRIA

[3]Friedrich-Alexander-University Erlangen-Nürnberg, Department of Fluid Mechanics,
Schloßplatz 4, 91054 Erlangen, GERMANY

[4]Medical University Innsbruck, Department of Radiology,
Anichstraße 35, 6020 Innsbruck, AUSTRIA

[5]Kardinal Schwarzenberg Hospital, Department of E.N.T.,
Kardinal-Schwarzenbergplatz 1, 5620 Schwarzach in Pongau, AUSTRIA

Abstract

In this study an own validated CFD code based on Lattice Boltzmann (LB) by Laser Doppler Anemometry (LDA) [1] is applied on a pre-, and postoperative CT dataset of a patient with nasal septum deviation to find parameters and identify surgically relevant regions. Therefore, pressure is the used variable and investigated on streamlines. There are regions with significant pressure drops that seem to be relevant for surgeries since on postoperative CT dataset on the same regions the crosssection is increased.

Introduction

Nasal septum deviation is a widespread disease at humans that cause difficulty to breathe through the nasal cavity. The common investigation techniques are rhinomanometry, acoustic rhinometry and endoscopy [2]. Unfortunately, based on the gained information not all surgeries are successful. New research fields try to use medical imaging techniques like Computer Tomography (CT) and Magnetic Resonance Tomography (MRT). Within a segmentation process [3] the flow through the nasal cavity is extracted from the head CT/MRT dataset to get the necessary geometrical information for the investigation. This is used for experiments including model generation to apply LDA measurements. Those results are used to validate Computational Fluid Dynamics (CFD) simulations, a tool that can calculate the flow (through to the nasal cavity) to find surgically relevant regions. The own research includes already a CFD-validated tool based on a simplified nasal cavity [1]. Information of the patient with nasal septum deviation is used to take geometrical data of a constriction to redesign a simple model. The maximum error between simulation and measurement is smaller than

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15% [1]. For the flow simulation LB (Lattice Boltzmann) and for the experimental analysis the LDA measurement technique LDA is used, respectively. The system includes one laser light source to detect one velocity component with high temporal resolution. To automate the process there are two servo motors featuring noninvasive plane measurement with high temporal resolution. From the simulation point of view, LB features simple and stable implementation on complex geometries at small Reynolds numbers. Due to parallelization of the code to reduce computational time the calculation on GPU with Sailfish CFD [4] is preferred. This preliminary work is the basis for this paper. The CFD simulation features results of pressure p and velocity $\vec{v}$.

LDA validated LB simulation

The starting point is a validated CFD simulation on a simplified nasal geometry presented at the GALA in Cottbus in 2016 [1]. A CT dataset of a patient with nasal septum deviation is used to generate a model [5] by inkjet printing technique (Connex 350) and use Plexiglas elements to achieve the needed optical accessibility for LDA. The measurement plane is defined on a surgically relevant position (Fig. 1 plane of interest). In Fig. 1 the general setup is depicted. The boundary condition is on the outlet a constant flow rate of 0.8 l/s. Respectively, on the inlets is a seeding generator to generate the tracer used to reflect the laser light with the Doppler frequency shift. In order to reduce optical noise, the model of the simplified nasal cavity is sealed by a glass pane.

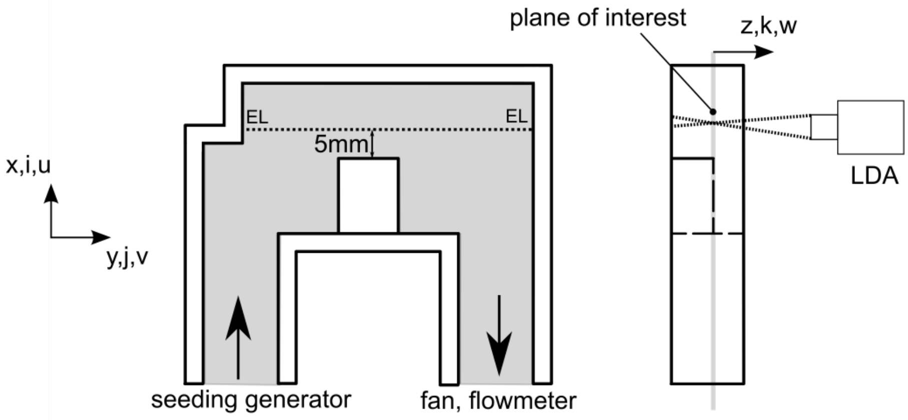

Fig. 1: LDA measurement setup of the simple nasal geometry with horizontal cut [1].

The plane of interest is investigated with a spatial resolution of 1 mm. Since the LDA system consists of only one laser light source, one measurement point must be evaluated repeatedly. In total there is the need to perform the measurement of every point twice to get the “velocity in plane”, three times to calculate the velocity magnitude. The optical accessibility to investigate the velocity component in z-direction is difficult and small; therefore it is not taken into account in this investigation. Additionally, for a quantitative investigation an Evaluation Line (EL) is positioned 5 mm apart from the constriction (narrow region) so that EL is outside the boundary layer region.

Fig. 2 shows a summary of the results. LDA is compared with the Finite Volume Method (FVM Ansys Fluent) – with the turbulence model realizable k-epsilon (enhanced wall treatment). Additionally, LB is used since on the complex nasal geometry it is computationally much easier and more stable to implement. Qualitatively, LB, LDA and FVM shows similar results, quantitatively the maximum error is smaller than 15%.

These results are used to develop a first approach to find relevant positions predict surgical intervention sites and eventually to increase the success outcome of surgeries (for the deviation of the nasal septum).

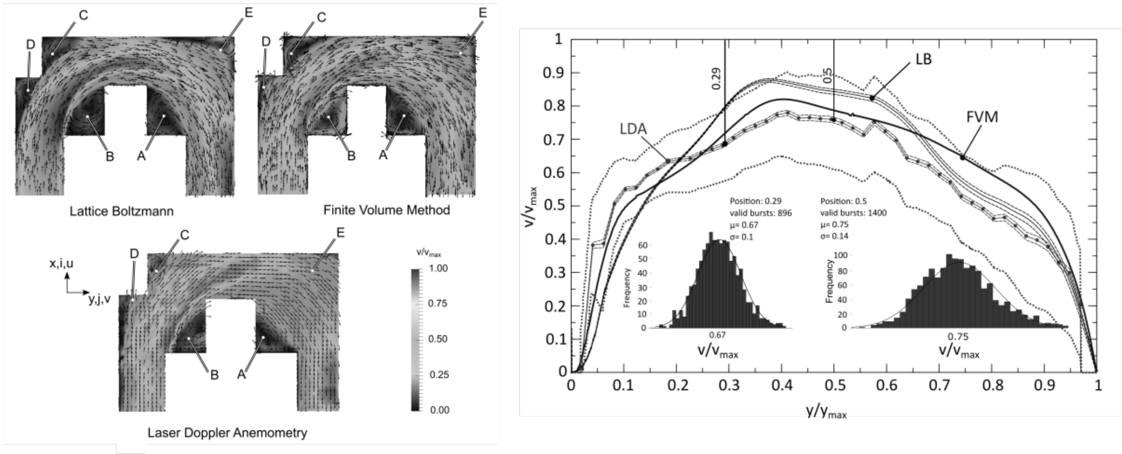

Fig. 2: Qualitative and quantitative comparison between LB simulation and LDA measurement of the simple nose model [1].

Segmentation of the CT datasets

For the presented investigation a pre-, and postoperative CT dataset of a patients head with nasal septum deviation is used. Images are acquired with Siemens Somatom CT with spatial resolution of 0.38 x 0.38 x 0.6 mm^3.

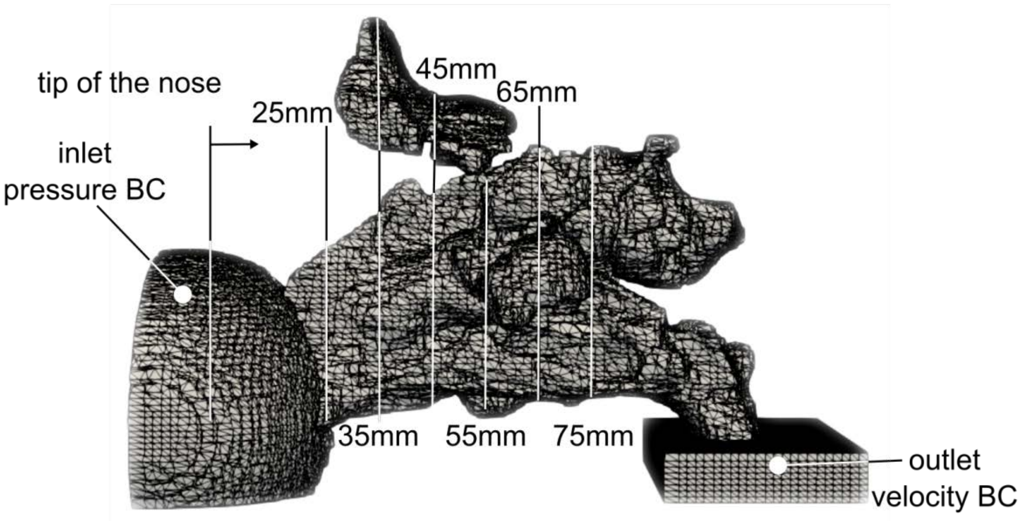

Fig. 3: Segmentation from CT to STL.

However, in this case the in-plane resolution is higher compared to the cranial-caudal direction. The grey value (CT slice) is related to the physical density so that one can distinguish between air, soft tissue and bones. The first step [3] is thresholding to select and use all voxels which Hounsfield Units corresponding to air (-1024 to -300 HU) inside the head. Therefore an inlet and outlet are defined. A lot of surgeries take place near the inlet of the two nostrils, therefore, this boundary condition is chosen carefully. A sphere, where the midpoint is set on the nasal tip is defined. The surface of the sphere is the inlet boundary condition of the simulation. In order to save GPU-RAM the sphere is limited in the boundary box of the CT dataset. On the outlet a rectangular cross-section is set so that it is simple to define a mass flow boundary condition by velocity on all outlet cells. In the final step the region growing algorithm takes only connected voxels (air) and delete all others. Finally, the selected voxels are saved as surface geometry (STL) which is later used for the lattice Boltzmann simulation. In Fig. 3 the segmentation result with the selected investigation planes is displayed.

Lattice Boltzmann simulation

The flow through the nasal cavity is simulated by the validated LB code [1]. The boundary condition on the outlet is taken from rhinomanometry to adjust constant flow rate which features much more stability (numerical divergence) than pressure BC. The surface of the sphere is set to ambient pressure. Since the flow is consisting of turbulent structures (Reynolds number is approx. 10 000), a LES turbulence model based on Smagorinsky [4] is used. The transient simulation is stopped when the flow is fully developed (0.025 seconds).

Optimization parameters

Global parameters give information about whether there is a constriction (narrow region), but not how to improve on these. The simplest one is the overall pressure drop between inlet and outlet. The higher the pressure drop, the more energy is needed for comfortable breathing. The second one is the flow rate calculation applied on both channels of the nasal cavity. This parameter can give information about the ratio between left and right side to detect whether there is only on one channel a problem. The flow rate is calculated by $\int \vec{v} \cdot \overrightarrow{df}$, where $\vec{f}$ is the surface normal vector with the length of the cross section area. Though, from medical point of view it is not a must that for healthy breathing on left and right side the same flow rate is needed.

As a local parameter pressure seems to be to good choice to find surgically relevant regions. Static pressure is not related to directions (scalar quantity in CFD), however, spatial derivatives are used to find changes in directions to detect big pressure drops. Therefore, the streamline investigation is introduced. A streamline is a line which is tangential to the calculated velocity vector field. From the Navier-Stokes equations [6] it is easy to see that there is only a flow ($\vec{v} \neq 0$), when there is a pressure gradient (without gravity). In the nasal cavity there are regions which are not mainly used for breathing (frontal sinus), there is no streamline and so it is not relevant for the surgery.

Results

Table 1 shows the global parameters of the simulation. The patient has a problem in breathing since on the right side since the flow rate (39%) is due to a nasal septum deviation smaller (see Fig. 4). Since it is an incompressible flow (small Mach number), in every cutting plane (see Fig. 3) the overall flow rate must be constant. As a reference the pressure drop of the preoperative simulation is set. In the postoperative CT dataset only 61% pressure is needed which results in much easier breathing. Additionally, after surgery the flow rate is nearly equal between left and right side.

Preoperative: Pressure drop: 100%		
Flow rate:	Left: 61%	Right: 39%
Postoperative: Pressure drop: 61%		
Flow rate:	Left: 51%	Right: 49%

Table 1: Results of global parameters of the simulation.

In Fig. 4 qualitative simulation results of pre-, postoperative CT datasets on the selected cutting planes are depicted. By the comparison of the crosssection in cutting plane 35 mm there is the most surgically relevant region. The color is the velocity magnitude which is the vectorial sum of the three components. Coronal investigation planes are defined in 10 mm distance, whereas the first one is 25 mm away from the nasal tip. From anatomical point of view ideally the septum should be a straight vertical plate in a healthy person. At the used patient CT dataset the septum is deformed.

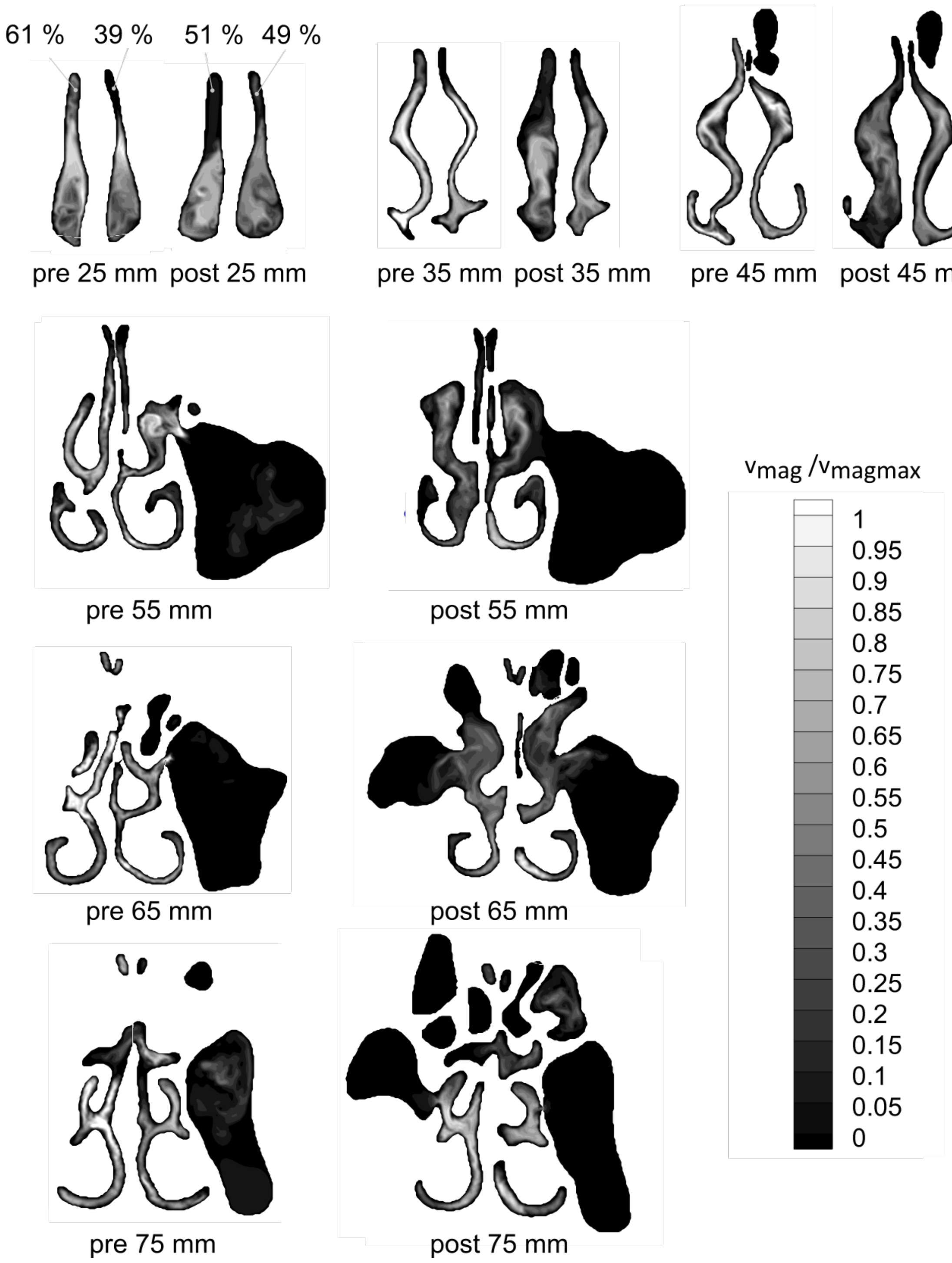

Fig. 4: Qualitative comparison of pre and postoperative lattice Boltzmann simulations. Color graph shows normalized velocity magnitude.

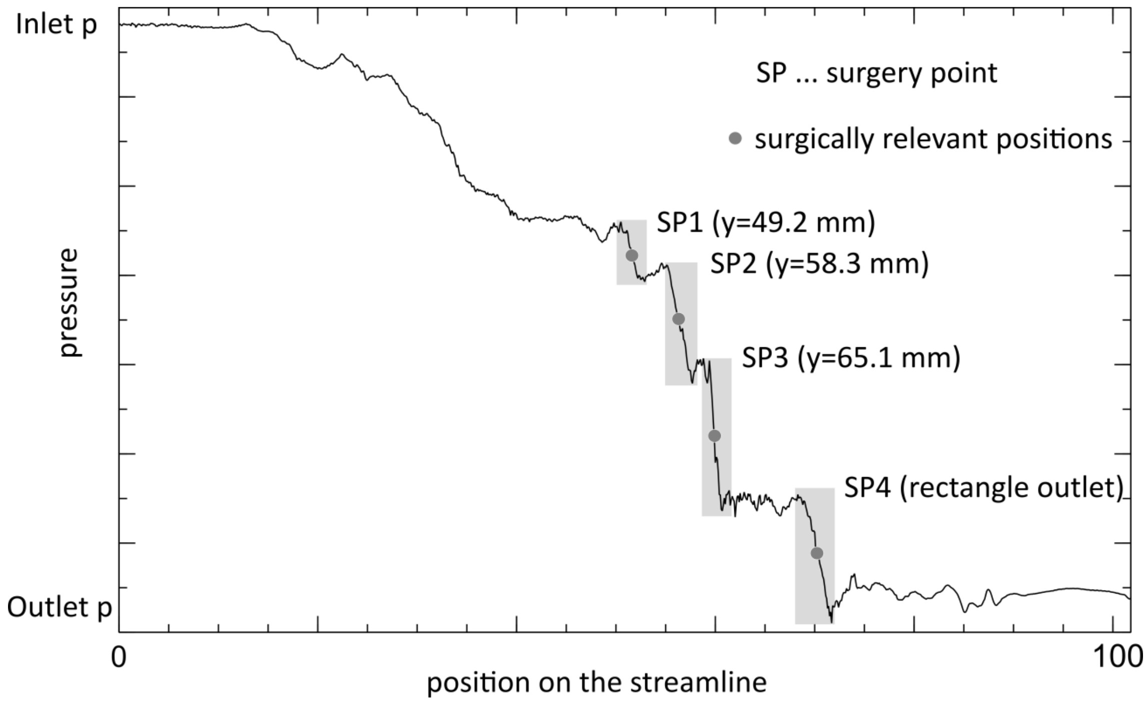

Fig. 5: Investigation of one streamline.

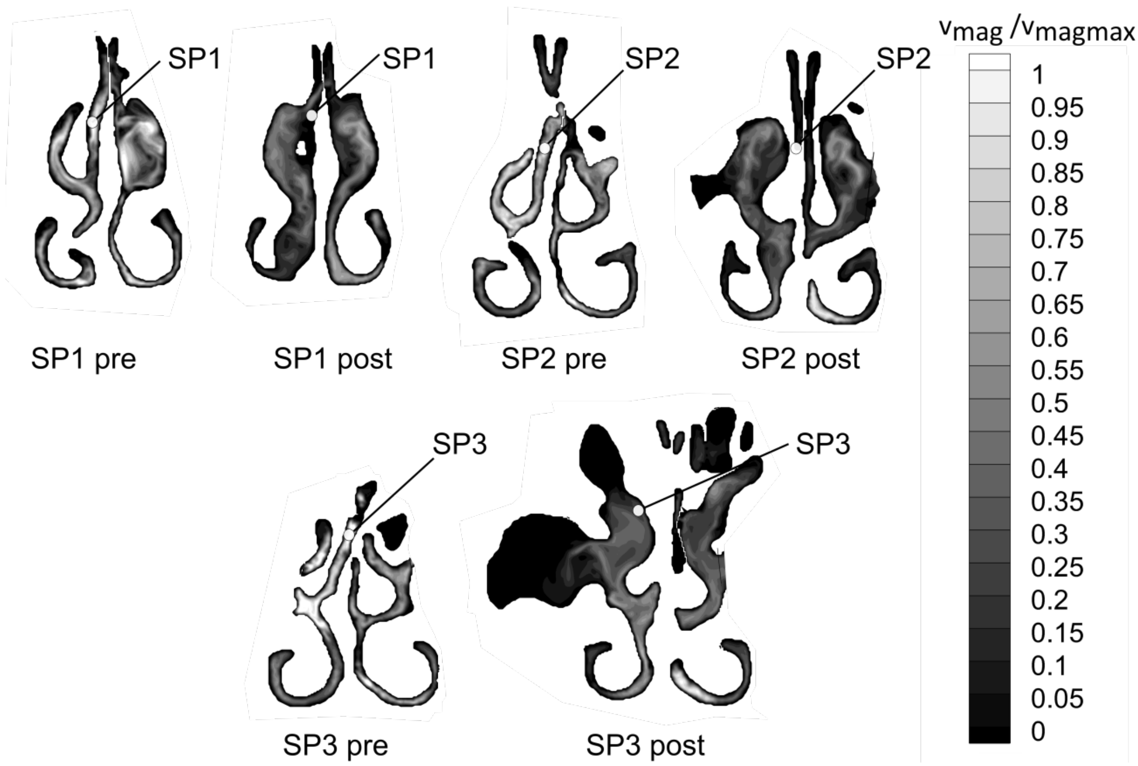

Fig. 6: Investigation of the flow at surgically relevant points.

Fig. 5 shows the investigation of one streamline. There is a continuous pressure drop from the inlet (the nostrils) to the outlet (pharynx). By visual inspection there are some regions where the pressure drop is high on a very small distance along the streamline which is marked as a surgery point (SP). A high pressure drop indicates a constriction; an increase of crosssection (surgery) would in this position improve breathing behavior. A comparison between pre-, and postoperative CFD simulation shows whether on this positions a surgery has an effect and therefore the surgery point is relevant. In corresponding Fig. 6 the coronal cutting planes include the surgically relevant positions. In those constriction zones are small crosssections, and therefore a relatively high velocity due to continuity equation. In all cutting planes (SP1, SP2 and SP3) there is an increase of cross-section visible, which results in a smaller maximum velocity. Therefore, in the postsurgical CT datasets the Reynolds number is smaller and the flow tends to have less turbulent structures which are more appropriate for breathing. In the postsurgical dataset SP2 and SP3 there is on the post CFD simulation no fluid domain. The reason is on one hand the surgery, on the other hand, the shape of the nasal cavity changes daily.

Discussion

The presented work shows the first idea to find surgically relevant positions inside the paranasal sinuses. The basis is a LDA validated CFD dataset. A streamline, which is a line tangential to the velocity vector field, is used to extract pressure from the CFD result. By visual inspection on the second half of the nasal cavity (inlet-outlet), there are big pressure drop regions. The results of SP1 to SP3 are investigated, SP4 is on the outlet and does not come from anatomical structure, and is therefore not surgically relevant. The comparison between pre- and postoperative CT datasets shows an increase of crossection, smaller maximum velocity, smaller Reynolds number and therefore less turbulent structures which is more appropriate for nasal breathing.

Outlook

The next step is to automate that step to find surgically relevant points on the streamline automatically. One streamline is not representative for the overall breathing process. There is the need to find the minimum amount of streamline starting points, that a further increase does not increase the surgically relevant volume of the patient.

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