Preparation of a Real Model of Nasal Cavities from Computed Tomography for Numerical Simulation

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Abstract. With improves in computing hardware and CFD methods, it is possible to work with more complex geometries. The aim of this study is to describe the preparation and creation of a model from CT scans for a numerical study of air flow into the nasal cavities.

Research background: The influence of pituitary tumor surgery on the change of geometric proportions of the nasal cavity is investigated in cooperation with the Neurosurgical Department.
Purpose of the article: In pituitary tumor surgery, the nasal cavity is used as an access route to the Sella turcica where the pituitary gland is located. Geometric changes occur during surgery. These changes in the geometry of the nasal cavities affect the air flow into the nasal cavities and the sense of the smell of the operated patients.
Methods: Based on CT scans of one patient, a procedure was created for creation of models of nasal cavities before and after surgery of pituitary tumor. The open-source software 3D Slicer was used for processing CT scans. Furthermore, the model before and after surgery was modified in CAD program Autodesk Inventor and program Ansys Space Claim. Meshing and subsequent solution of the finite volume method was solved in program Ansys Fluent 2021 R1.
Findings & Value added: The models were created considering the anatomical structure of the cavities and were aligned into corresponding coordinate systems. Despite of the efforts to align the planes, inaccuracies occur between the planes. However, the results are comparable.

Keywords: *Nasal Cavity; CT scans; CFD; Numerical study; Adenomas*

1. Introduction

The expansion of the possibilities of using real geometries in fluid flow research have been possible as a consequence of the development of computational technology. Thanks to more powerful computational technology, it is possible to process more complex geometries,

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which would have been too complicated and laborious to create just a few years ago. This can be used not only in numerical studies, but also in experimental measurements.

In the framework of cooperation with the Neurosurgical Department of the Central Military Hospital, a problem arose with the creation of real models from Computed Tomography (CT) scans. In the case of pituitary adenoma surgery, the geometry of the patient's nasal cavities is changed given that the nasal cavity is used as an access road to the Sella turcica where the pituitary gland is located. The influence of surgery on the change of geometry through the passage of surgical instruments is therefore crucial. The change of the nasal cavity after surgery affects the change in air flow through the nasal cavities and may also affect olfactory functions [1, 2].

In previous years, studies have been developed to reach a general model of nasal cavity. These articles were based on a statistical approach and the processing of images of a large number of patients (16 and more). This approach is interesting, but it is not possible to use it for the purpose of determining the effect of adenoma surgery on air flow through the nasal cavities. This article will therefore describe the process of designing two models for numerical study where the two models will be compared before and after surgery of one patient [3-5].

2. Methods

2.1 CT images processing

The patient's data from which the model was created were obtained from a Neurosurgical Department. Both Magnetic Resonance Imaging (MRI) and CT images were processed by the open-source 3D Slicer program. This program was used for imaging, segmentation of the model and changing the coordinate system of the images.

First, both MRI and CT images were imported to the 3D Slicer program. Comparing the data from different sources, the CT images were better. This is due to the properties of the investigative methods. In general, the MRI data had worse resolution compared to the CT and contained noise.

After importing the CT data into the Slicer, a threshold function was used to create a three-dimensional body. The threshold function works with intensity range, and it is possible to select a part of the skull, brain, soft tissue, or cavity. In this study, cavities were selected to be further worked with. The volume created was adjusted by simple functions of erase, scissors, and paint. The erase and paint functions remove (create) parts of the model in the individual slices of which the visualization is made of. Conversely, the scissors' function can remove or add volume in several slices at once. These functions allow to remove secondary nasal cavities and other parts, that do not affect the change in geometry before and after surgery. Modifications of the model in the Slicer program and individual removal of anatomical parts in both models were consulted with the Neurosurgery Department.

An important part of the process of creating the nasal cavity model is the comparison of the coordinate systems between model before and after the adenoma surgery. The results of the pressure and velocity fields are presented in the coronary planes. In order to compare the pressure and velocity fields of the two models, the coordinate systems need to be unified.

Although the effort to compare coordinate systems is great, the process has not yet been improved enough to achieve an identical comparison. Figure 1 shows the best result of the comparison that has been achieved. The two models differ in some parts even from an anatomical point of view. This is due to the change in geometry after the surgery.

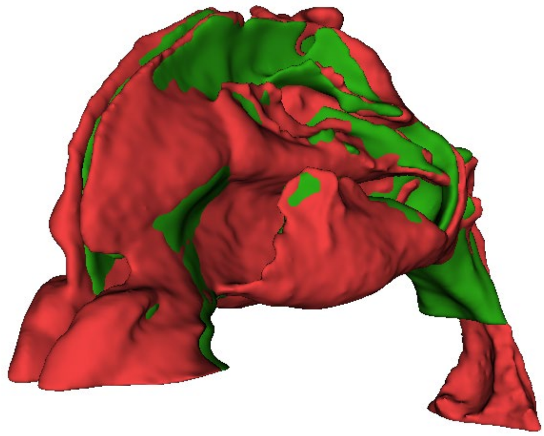

Fig. 1. Transformation of the coordinate system (green – before surgery; red – after surgery).

The last part of creating a model of nasal cavities in Slicer is smoothing the model. The 3D Slicer automatically smooths surfaces when displaying the created volume. Gaussian smoothing is used for this purpose. At this point it is necessary to mention an article [6] in which the authors compare various errors in the creation of the models. The study is concerned with comparing the experimental model and the model that is created for the numerical study. They compare the wall roughness, caused by the inaccuracy of the casting used for the experimental model, and the surface smoothing. Surface smoothing is caused by the resolution of MRI or CT data and the approximation of the model to real geometry. The model in the article is smoothed by two smoothing factors. The article shows that small smoothing can help reduce pressure resistance, however, with high smoothing the pressure loss of the flowing air decreases too much. In the case of this article, the model uses minimal smoothing of the model by Gaussian smoothing of 0.3, so that there is as little difference as possible from the real nasal cavities.

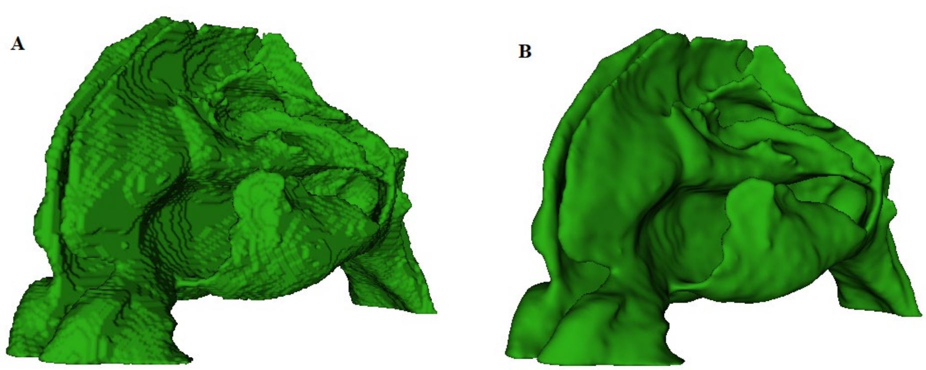

Fig. 2. Smoothing of the model – A without smoothing; B with smoothing 0.3.

After modifications in 3D Slicer, the model was converted into CAD software Autodesk Inventor 2018. It is included in the whole production process mainly for simple alignment of the nostril surfaces and the surface in the nasopharynx area. For the nostril area, only planes parallel to the coordinate system of the model were used. In the area behind the nasopharynx, the alignment of the model was a bit more complicated. CT scans are mainly influenced by the position in which the patient is located during the examination. For unity between the

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models before and after the surgery, a plane parallel to the Chamberlain line was selected. Chamberlain line is a radiologically defined plane between the posterior part of the hard palate and the posterior point of foramen magnum. More detailed description is in article [7]. The next step after alignment of the nostrils and the plane in the nasopharynx area is to create a starting length to meet the theoretical conditions of fluid mechanics. The calculation thus creates a speed profile, corresponding to the second-order curve. To create the starting length of the model, the plane of the nasopharynx area is used, which is subsequently labelled as outlet. The created areas in the nostril area are further labelled as inlet.

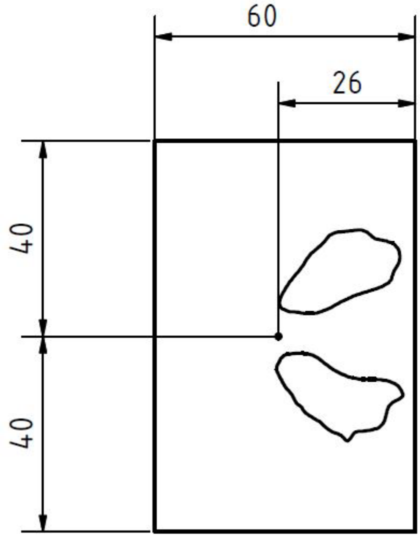

Fig. 3. Sketch for creating cube before nostrils.

A cube is created in front of the nostrils, on which a pressure boundary condition is prescribed in the solution. A sketch of this object is shown in Figure 3. The sketch is extruded in the next step and a cube is created. The top wall of the cube is referred as wall boundary condition and the side walls are referred to as the inlet boundary condition.

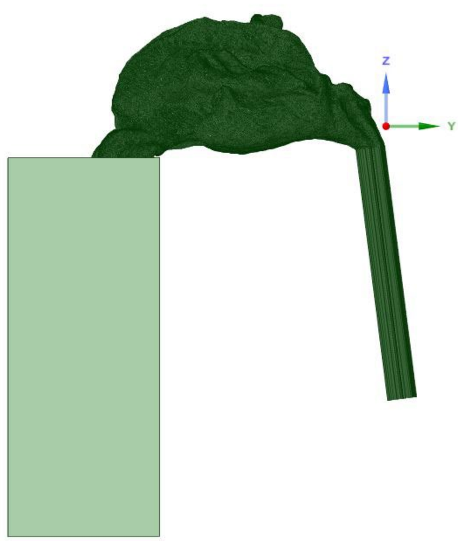

Fig. 4. Model of nasal cavity.

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2.2 Meshing

The meshing of the nasal cavity model was done in Ansys Fluent 2021 R1. Prior to the meshing, the model was modified in Space Claim, where minor geometry errors were corrected, and areas were divided into facet zones. Space Claim was mainly used for compatibility with program Ansys Fluent, which is further used for meshing and solution. The program is also suitable for faster managing the model, thus faster division of the model into facet zones and corrections of errors such as intersecting areas or holes in the model.
For meshing the models before and after the pituitary tumour surgery were used the same parameters. The global cell size of the surface mesh was 5-10 mm. The local cell size of 1 mm was used for the surface mesh of nasal cavity zone. The volume mesh was constructed with polyhedral cells, the size of which was set to 5 mm. The model before the surgery contained 0.72 million cells and the model after the surgery was made of 0.745 million cells. The two mesh were selected based on a previous study comparing the results of four meshes with different number of cells. The model after the surgery is expected to have more cells. The anatomy was affected in the area of sphenoidal sinus and some passages were enlarged. Therefore, these parts of the model could not be erased from the model after the surgery in the affected area as they were in the model before the surgery.

2.3 Boundary condition

As described at the end of the 2.1 CT images processing, parts of the model have been created in Autodesk Inventor to prescribe boundary conditions. A cube has been created in front of the nostrils, on which the side and bottom walls are marked as inlet. On the inlet planes, a pressure inlet boundary condition is prescribed with zero difference from total pressure. After creating a starting length behind the nasopharynx, the extruded plane is marked as outlet. On the outlet, a mass flow outlet boundary condition is prescribed. On all other surfaces, wall boundary conditions are prescribed, where the flow rate is zero. On the Figure 5, a model of nasal cavity with a schematic representation of these boundary conditions is illustrated.

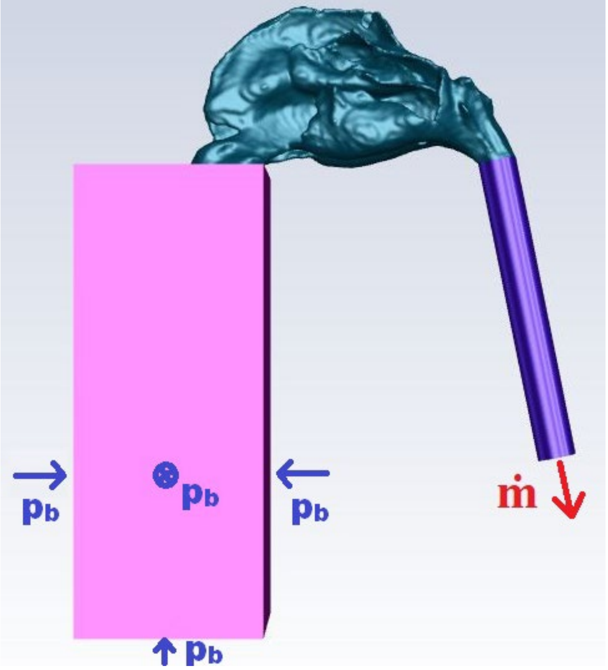

Fig. 5. Schematic representation of boundary conditions.

The numerical calculation was performed for steady flow. The Figure 6 shows the mass flow during the human respiratory cycle. Individual red points indicate the mass flow values that were prescribed for individual calculations on the outlet.

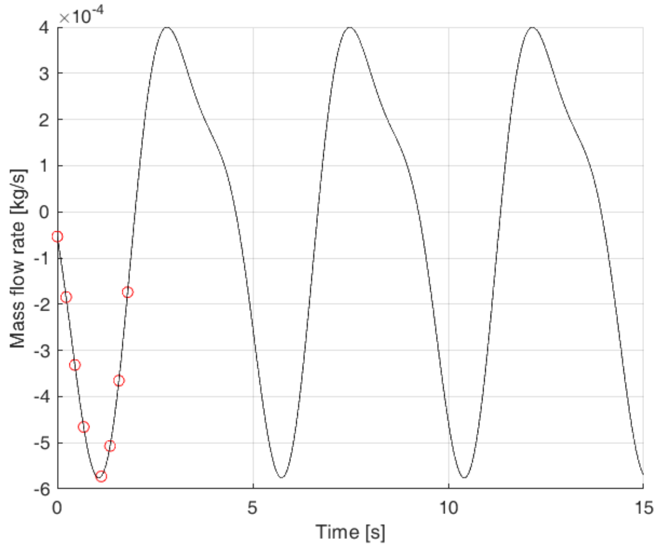

Fig. 6. Mass flow rate during human respiratory cycle.

2.4 Solution

The numerical simulation of air flow in the inspiration part of breathing cycle was performed under steady flow conditions. A viscous laminar computational model was used on both models before and after the adenoma surgery and the used solver was pressure based. The pressure gradient was calculated by second order function and the momentum gradient by a second order upwind scheme [8-10].

3. Results

In model were created planes to plot the results of the numerical study. The Y-planes are created parallel to the coronary planes. The schematic representation of the created planes can be seen on the Figure 7. The blue area is the olfactory area.

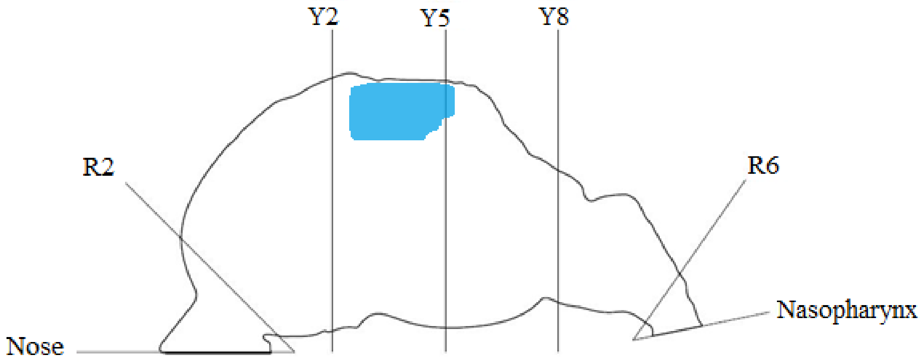

Fig. 7. Schematic representation of planes for displaying result.

This paper presents the results of a numerical study on the plane Y5 for a steady solution at maximum mass flow rate. The planes were created in the model before and after adenoma surgery, in the same distance from the beginning of the coordinate system.

Pressure loss, or pressure resistance, is a very significant factor in fluid dynamics. Therefore, pressure loss was investigated in the nasal cavity model. In both models, static pressure values were calculated on the planes of the nasopharynx and nostrils and subtracted from each other. This determined the pressure loss of the entire model.

Table 1. Pressure loss in nasal cavity model for maximal mass flow rate.

Plane	**Nose**	**Nasopharynx**	
	Static pressure [Pa]	**Static pressure [Pa]**	**Pressure difference [Pa]**
Before surgery	-0.07027	- 1.0210	- 0.950730
After surgery	- 0.04848	- 0.7989	- 0.750420

On the Figure 8 and Figure 9 pressure and velocity fields are displayed. Of the left, there are fields of model before surgery and on the right side are results on plane Y5 after surgery. When comparing pressure fields before and after surgery, it is possible to notice an increase in static pressure throughout the cross-section. For the results of the velocity fields, it is possible to notice much smaller differences in values. The most noticeable differences are in the middle part of the velocity field. Maximum values of both models are located there, although velocity values in the model before surgery are higher. Furthermore, there is a decrease in velocity values in the upper area of the plane Y5 in model after adenoma surgery. This occurs probably due to an increase of volume in the model after the surgery.

Static pressure field

Before surgery	After surgery

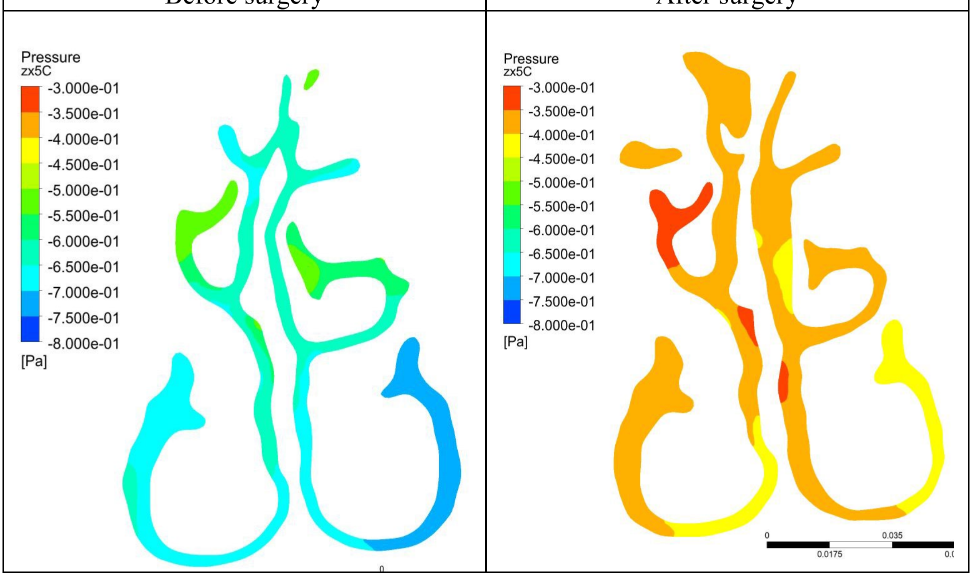

Fig. 8. Results of static pressure field displayed on plane Y5 for maximal mass flow rate.

Velocity field	
Before surgery	After surgery

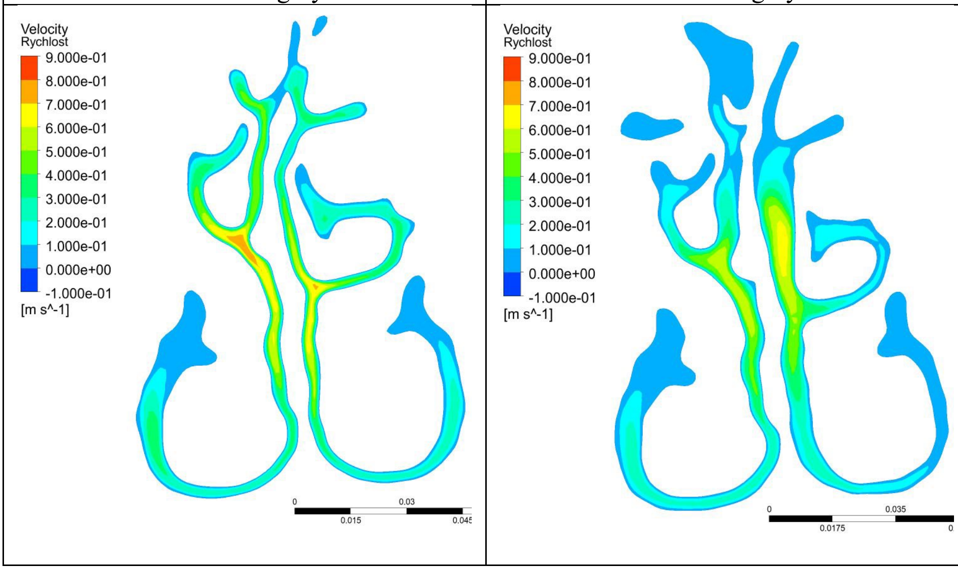

Fig. 9. Result of velocity field displayed on plane Y5 for maximal mass flow rate.

4. Discussion

The main objective of this article is to create a procedure for the creation of realistic models of nasal cavities. Models of nasal cavities were created according to the above procedure regarding the change in the anatomy of nasal cavities after the adenoma surgery. In chapter 3. Results are presented the results of numerical study in the steady flow mode for maximum value of mass flow rate during inhale part of breathing cycle on the plane Y5. In the Results section it is possible to observe not only the velocity and pressure fields, but also the changes in geometry between models.

From the presented results, it may appear that there are large changes in both pressure and velocity fields. It is true that the static pressure in the whole model increased significantly after surgery, but it is important to note the change in cross-section area between the models. In the model after surgery, there is an expansion of the middle meatus due to the passage of surgical instruments. That means the local dimensions of models differ, but when comparing the global dimensions of the model before and after the surgery, there is no greater deviation than 2.5 % in the basic dimensions.

Changes in the nasal cavity appear day by day. These changes are hormonally affected, they are not perceived. This can also affect the differences between the models of patients before and after surgery, because when examined by CT or MRI, patients can be at different stages of this cycle.

An important part of the research on the influence of adenomas surgery on the change in geometry is to compare the results between the two models. Without comparing the models into the same coordinate systems, it would be very difficult to create planes at the same place of the models. Among other things, setting the same coordinate systems provides a faster possibility of creating planes for presenting the results.

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