

3D Computational Modelling of Nasal Cavity Soft Tissue Deformation for Preoperative Planning and Surgical Training

Maksym Tymkovych^a, Oleg Avrunin^{*a}, Iryna Yepifanova^b, Karina Selivanova^a, Saltanat Amirgaliyeva^c, Yana Nosova^a, Nataliia Shushliapina^d, Oleksandr Avrunin^a, Viktoriia Fedotova^e, Bohdan Pryvalov^a, Żaklin Grądz^f

^aKharkiv National University of Radio Electronics, 14 Nauky avenue, 61166 Kharkiv, Ukraine; ^bVinnytsia National Technical University, Vinnytsia, Ukraine; ^cInstitute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan; ^dKharkiv National Medical University, 4 Nauky avenue, 61022 Kharkiv, Ukraine; ^eNational Pirogov Medical University Vinnytsia, Ukraine; ^fDepartment of Electronics and Information Technology, Lublin University of Technology, Nadbystrzycka 38D, Lublin, Poland

ABSTRACT

Begin the abstract two lines below author names and addresses. The abstract summarizes key findings in the paper. It is a paragraph of 250 words or less. The abstract section should be self-contained (i.e., no numerical references) and substantive in nature, presenting concisely the objectives, methodology used, results obtained, and their significance. Avoid use of equations and complex fractions. Adequate respiratory function, which depends on nasal airway patency, is critical for human health. Disorders affecting the nasal cavity often require surgical intervention to restore normal airflow, but its complex anatomy demands precise preoperative planning. This study describes an approach to simulate soft tissue deformation in the nasal cavity using the SOFA Framework, an open-source biomechanical modeling platform. By integrating patient-specific CT data, we demonstrate the framework's ability to simulate surgical outcomes, focusing on the biomechanical behavior of anatomically accurate structures. The results highlight the potential of this approach to enhance surgical training and preoperative strategy planning. Real-time implementation of such simulations could reduce intraoperative risks and improve postoperative outcomes, contributing to personalized treatment strategies in otolaryngology.

Keywords: CT image segmentation, deformable biomechanical modeling, human health, personalized treatment, precision medicine, SOFA Framework, soft tissue deformation, surgical 3D planning

1. INTRODUCTION

The respiratory system is one of the main human systems that ensures normal functioning. It maintains the gas exchange of internal organs with the external environment, which enables the supply of oxygen, which is necessary for energy and other biochemical processes in the human body¹⁻².

Structurally, the upper respiratory tract in general, and the nasal passages in particular, are the main elements of the respiratory system, involved in air heating, air filtration, air humidification, protection against infections, regulation of air flow, and odor sensing. Thus, their contribution to the overall health and well-being of a person is immense³⁻⁶.

A significant part of nasal breathing disorders is associated with a disorder or deviation of the internal anatomical structures of the nose from the normal ones. Such problems include sinusitis, otitis media, pharyngotonsillitis, apnea and other nasal breathing disorders, which may be accompanied by difficulty in nasal breathing, discharge, impaired olfactory function, fatigue, headache, etc⁷⁻⁹.

Surgical intervention¹⁰, although an invasive method, is in many cases one of the most effective, and even the only solution that can ensure the normal functioning of nasal breathing for a patient^{9,11}. Such a surgical intervention is associated with a large number of difficulties, including the assessment of the required target shape (which ensures the normal functioning of the system, organ, area, etc.) and the necessary deformations, resections and other manipulations

*oleh.avrunin@nure.ua

to bring the current state to the target. Modeling such transformations is associated with significant difficulties, as simulation requires realistic deformations in accordance with biological structures¹²⁻¹⁵.

2. MATERIALS AND METHODS

The purpose of this work is to investigate the possibility of using the modern SOFA Framework¹⁶⁻¹⁸ for planning and training of nasal cavity surgeries, and, as a result, to improve the quality of surgical interventions¹⁹.

Selection and evaluation of the resulting three-dimensional model is carried out in accordance with the objective function of a particular task. In the case of providing the required nose resistance, it is possible to use CFD methods²⁰⁻²², which allow estimating specific numerical values based on a mathematical model.

Three-dimensional models of anatomical structures (M) can be represented as a mesh of triangles (1) or as a tetrahedral mesh (2).

$$M_{tri} = (V, F), \quad (1)$$

where $V \in R^3$; F is a set of faces.

$$M_{tetra} = (V, T), \quad (2)$$

where T is a set of tetrahedra (each tetrahedron $t \in T$ is defined by four vertices $\{v_1, v_2, v_3, v_4\} \in V$).

An elementary action (A), or an manipulation that modifies a model, can be, in the simplest case, a rigid transformation that transforms the vertices of a three-dimensional model M :

$$A_\theta(v) = Rv + t, \quad (3)$$

where R is the rotation matrix; t is the displacement vector; $v \in V$ is the vertex of a three-dimensional model; A_θ is a parameterized function; $\theta = (R, t)$.

In the more complex case considered in this paper, an elementary action (A) is a deformation of a three-dimensional model in accordance with the physical properties of the anatomical structure.

In the future, it is planned to supplement the possible actions with resections to simulate surgical interventions to the fullest extent possible.

A sequence of elementary actions forms an operational intervention $\{A_1, \dots, A_n\}$, where

$$M_k = A_k(M_{k-1}), k=1, 2, \dots, n. \quad (4)$$

This sequence should ensure that M_n is close to M_{target} .

To determine the proximity of surfaces, it is possible to use the Hausdorff distance (L_H) for surfaces.

Thus, it is possible to optimize the number of steps (actions) to reduce manipulations during surgery and ensure the required accuracy:

$$\min_{\{A_1, \dots, A_n\}} L_H(M_n, M_{target}) + \lambda \sum C(A_k), \quad (5)$$

where $\lambda > 0$ is the regularization coefficient.

In general, the entire research process conducted during the study can be described using the following diagram (Fig. 1)

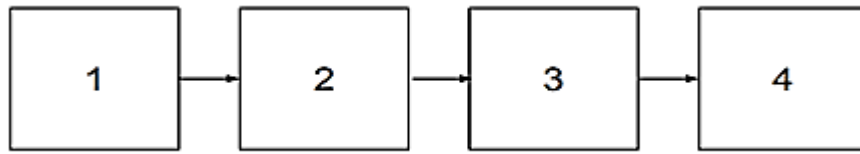


Figure 1. Generalized stages of the study: 1 – Data preparation; 2 – Simulation initialization; 3 – Simulation step(s); 4 – Result evaluation

As you can see from the figure, the first and most important stage is data preparation. Taking into account the requirements of the SOFA Framework regarding the type of input data, its structure, etc., it is necessary to prepare the data. The stages of the process of preliminary data preparation for the simulation are shown in Fig. 2.

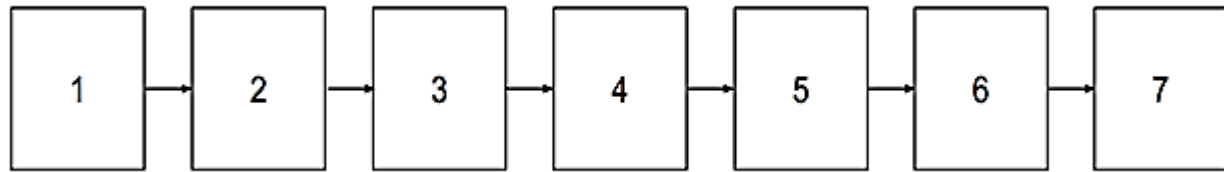


Figure 2. Stages of the data preparation process: 1 – DICOM slice (Raster data); 2 – Airway segmentation (binarization); 3 – Region selection (cropping); 4 – Image stacking; 5 – Triangle mesh generation; 6 – Triangle mesh optimization; 7 – Tetrahedral mesh generation

For the study, 2d computed tomography slices in the frontal projection, presented in DICOM format, were used as input data. Moreover, the sections were used both in the normal state (Fig. 3 a), various kinds of nasal passages disorders (Fig. 3 b, c, d), and the results of postoperative (Fig. 3 e) examinations⁹. The use of 2D sections, rather than complex three-dimensional structures, allows us to simplify the study to some extent in order to completely move on to solving the problem in full three-dimensional space with complex geometry in the future.

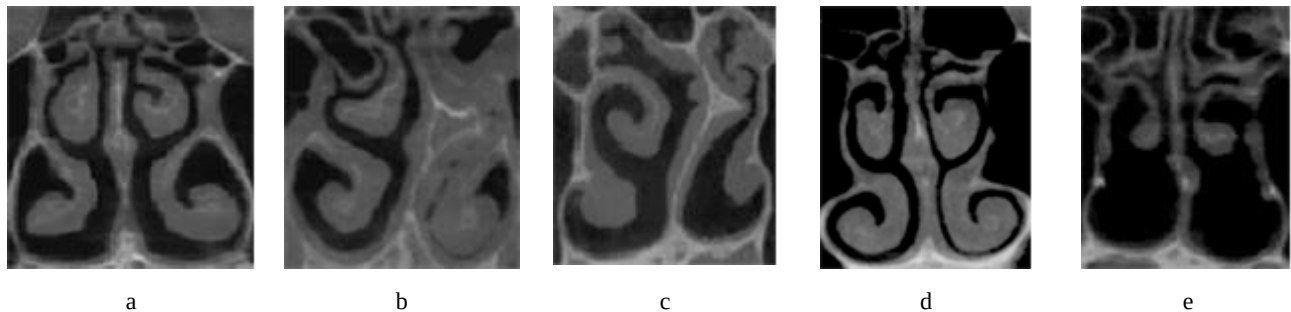


Figure 3. Frontal CT scans: (a) – normal (b) – curvature of the nasal septum to the left in the middle section; (c) – curvature of the nasal septum to the left in the posterior part; (d) – consequences of chronic rhinosinusitis; (e) – empty nose syndrome after conchotomy-bilateral removal of the lower shells⁹

To form a three-dimensional model of the slice, each of the slices was segmented (Fig. 4) using threshold segmentation²³.



Figure 4. Segmented frontal CT slices

In addition, it was decided to use additional synthetic sections to test the simulations on them. To do this, two binary sections were synthesized, one of which is two concentric disks of the same radius (Fig. 5a), and the other is two concentric disks with different internal radii and vertical and horizontal cross-sections (Fig. 5b).



Figure 5. Synthetic frontal binary slices: (a) – synthetic norma; (b) – synthetic pathology with preliminary incisions

To achieve volume, each of these slices-images (Figs. 4-5) is formed into a voxel volume by copying and stacking copies along the Z-axis (Fig. 6)

Transformation of the obtained volume into a polygonal format, understandable to most computer graphics applications, a 3D model format that describes the surface of the object under study using polygons (usually triangles), was carried out in script mode using the skimage library²⁴. This set of tools contains a significant number of image processing algorithms, including volume processing using the Marching Cubes algorithm²⁵.

The result of the Marching Cubes algorithm is shown in Fig. 7. Moreover, Fig. 7 b is shown at high magnification, because otherwise the polygonal mesh cannot be seen.



Figure 6. Illustration of voxel model formation based on binary slice images

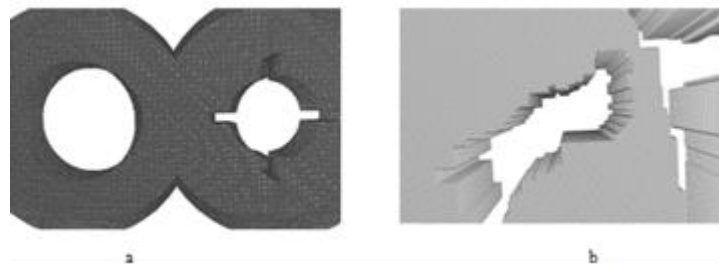


Figure 7. The result of the Marching Cubes algorithm in generating a polygonal mesh: (a) – polygonal mesh of synthetic pathology with preliminary incisions; (b) – polygonal grid of the norm

The result of generating a polygonal surface is not optimal in terms of the number of vertices and the number of triangles. Further algorithms for both visualization and tetrahedral mesh generation work better with more optimized three-dimensional models. That is why, to solve this problem, in GUI mode, we used the MeshLab²⁶ software application, which contains a large number of optimization, simplification, cleaning, etc. algorithms; and in script mode, its equivalent - the pymeshlab Python library, that contains all the same functionality. The algorithm used to simplify the polygonal mesh was “Simplification: Quadric Edge Collapse Decimation”²⁷.

The results of the algorithm are shown in Fig. 8 a, b, c, d. It is important to be careful, because during simplification, there may be cases of modification of the surface of the anatomical structure, in which the surface does not correspond to the initial data, and the simulation will become impossible. In addition, there may be cases of invalid self-intersecting polygons. To deal with that, it is necessary to detect such polygons, remove them, and fill in the resulting “holes” in the three-dimensional surface. This task is also performed using the MeshLab tool.

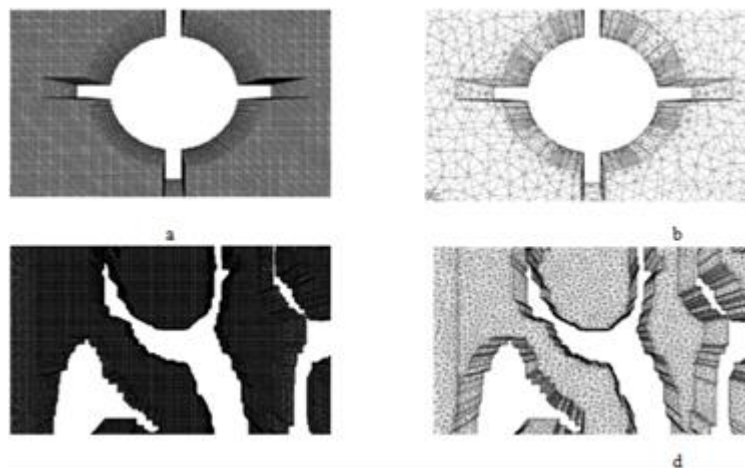


Figure 8. The result of the “Simplification:Quadric Edge Collapse Decimation” algorithm for simplifying a polygonal mesh: a – polygonal mesh of synthetic pathology with preliminary incisions before processing; b – polygonal mesh of synthetic pathology with preliminary incisions after processing; c – polygonal mesh of the norm before processing; d – polygonal mesh of the norm after processing

Depending on the case, the number of both unique surface vertices and the number of surface polygons has significantly decreased.

The next step, as mentioned above, is the generation of a tetrahedral mesh. This three-dimensional model describes not only the surface, but also the internal structure of the surface itself, due to the minimal tetrahedral elements. These elements allow to describe the topology of interaction between the volume elements, which is very important in deformation simulation. For this task, we used the specialized software gmsh²⁸⁻²⁹. In addition, gmsh has built-in algorithms for optimizing tetrahedral meshes. An example of a generated tetrahedral mesh is shown in Fig. 9.

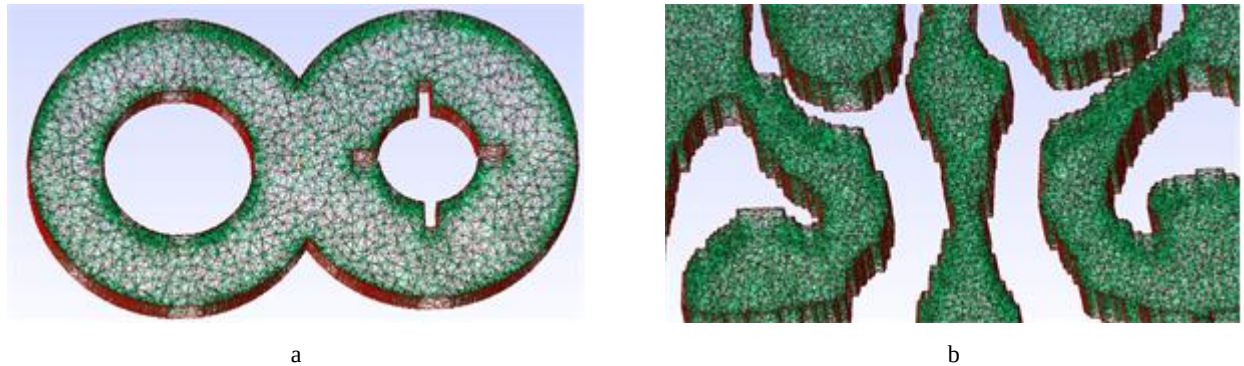


Figure 9. Result of the generation algorithm of tetrahedral mesh (edges of the boundary are marked in red, edges of internal connections are marked in green): a – tetrahedral mesh of synthetic pathology with preliminary incisions; b – tetrahedral mesh of the norm

The obtained data of both the polygonal surface and the generated tetrahedral mesh are used as input for further simulation of deformation of the nasal cavity tissues.

For the simulation, we used the SOFA Framework, which is a free tool with wide capabilities. Its use has a special place in the simulation of biological tissue deformation, because this was one of the primary ideas in its development.

The task of initializing the simulation is to load and position the anatomical structures to be simulated, fix certain elements of the anatomical structures, apply the necessary forces to the points of interest, etc. It should be noted that this is a simplified formulation of initialization, because the system requires precise configuration of the structures that conduct the simulation, perform the computation, perform the necessary conversions, etc.

Fig. 10 shows a simplified visualization of such initialization.

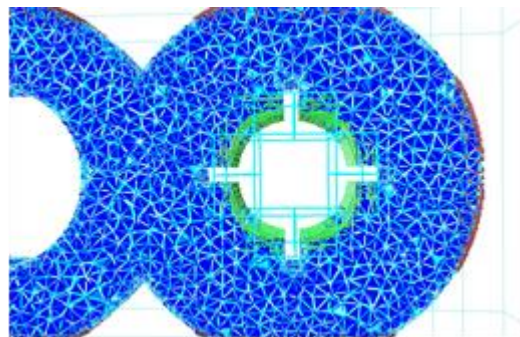


Figure 10. Simplified visualization of the initialized scene for synthetic pathology with preliminary incisions

The figure shows a tetrahedral mesh in the SOFA Framework environment. Bounding boxes surrounding the object under study represent the condition for fixing the mesh elements in space and correspond to the conditional connection of the deformable anatomical structure to the bones (non-deformable objects). Each such fixation is represented by a brown dot.

Tissue deformation is simulated under the influence of external forces. For this purpose, in this case, 8 multidirectional forces (indicated by green arrows) are generated and applied to different parts of the anatomical structure (bold bounding boxes). The choice of the direction and areas of application is made in accordance with the assumption of optimal application.

Thus, using these adjustments and constraints, taking into account the properties of the materials, it is possible to simulate the deformation in accordance with the mathematical model used.

Then, we can designate the initial three-dimensional model as M_0 , and the three-dimensional model whose shape we want to achieve as M_{target} . Moreover, M_{target} should correspond to the shape that optimally fulfills the functional

properties of the anatomical structure. In the case of the upper respiratory tract, as mentioned above, this means providing the necessary airflow resistance of the nasal passages (or rather the area), providing the necessary air heating (due to the contact of the studied surface saturated with blood with air), providing the necessary air humidification (due to the same contact of the moistened surface with air), etc.

3. RESEARCH RESULTS AND DISCUSSION

Taking into account the above-described conditions of the initialized scene (Fig. 10), we performed physical modeling of such a synthetic scene (Fig. 11) using the SOFA Framework.

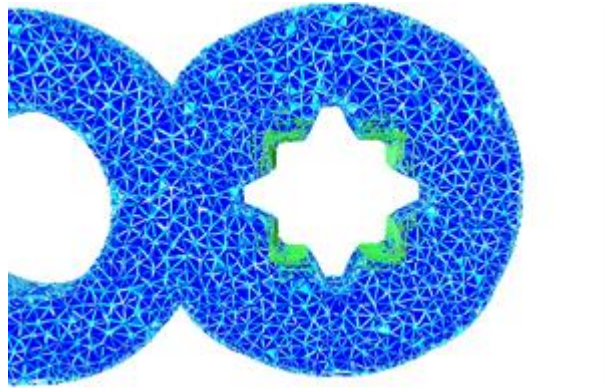


Figure 11. Simulation results of a scene with deformation of a synthetic pathology with preliminary incisions

The modeling results clearly show that the use of applied forces is not sufficient to achieve the desired effect. To provide the model with the desired shape, it is necessary to apply additional forces, or rather a force gradient, which will provide the required “ideal” result.

Simulations for other real cases were also performed (Fig. 12), which demonstrate the importance of using these approaches in planning surgical interventions and modeling the functional results of surgical interventions on the human upper respiratory system using CFD methods.

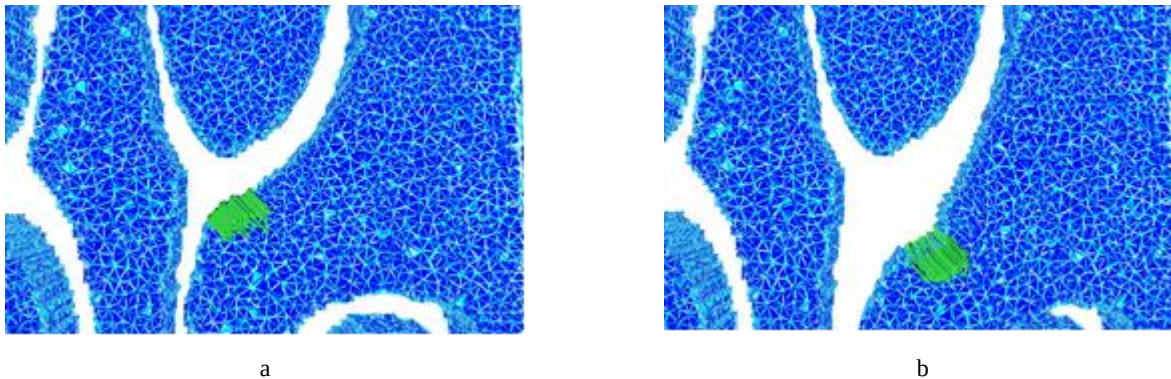


Figure 12. Simulation results of a scene with deformation (Fig. 4 d): (a) – area before deformation; (b) – area after deformation

4. CONCLUSIONS

As a result of the study, a three-dimensional reconstruction of the nasal airways in normal, pathological and postoperative conditions was performed. In addition, three-dimensional data were reconstructed for the synthetic case of “pathology”. On the basis of the obtained models, simulation studies of tissue deformation under external forces were carried out, depending on the desired result. The results obtained indicate the efficiency of the approach and the importance of using this method in preoperative planning.

The mathematical formalization of the surgical intervention and its relation to the simulations were carried out. Such actions may further allow optimization of the surgical intervention.

The next step in the study is to consider not only one type of tissue during deformation. Also, joints directly with bone tissue should be used as boundary conditions. An important component that requires considerable research is the combination of results with CFD modeling in the evaluation of the obtained results.

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