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An Interactive, Patient-Specific Virtual Surgical Planning System for Upper Airway Obstruction Treatments

Rachel B. Clipp, PhD [Member, IEEE],

Kitware, Inc., Carrboro, NC 27510

Jared Vicory, PhD,

Kitware, Inc., Carrboro, NC 27510

Samantha Horvath, PhD,

Kitware, Inc., Carrboro, NC 27510

Sorin Mitran, PhD,

University of North-Carolina-Chapel Hill, NC, USA.

Julia S. Kimbell, PhD,

University of North-Carolina-Chapel Hill, NC, USA.

John S. Rhee, MD, MPH, and

Medical College of Wisconsin, Milwaukee, WI 53226 USA.

Andinet Enquobahrie, PhD

Kitware, Inc., Carrboro, NC 27510

Abstract

Upper airway obstructions leading to difficulty breathing are significant problems that often require surgery to improve patient quality of life. However, these surgeries often have poor outcomes with little symptom improvement. This paper outlines the design of an interactive, patient-specific virtual surgical planning system that uses patient CT scans to generate three-dimensional representations of the airways and incorporates computational fluid dynamics (CFD) as a part of the surgical planning process. Individualized virtual surgeries can be performed by editing these models, which are then analyzed using CFD to compare pre- and post- surgery flow characteristics to assess patient symptom improvement. The prototype system shows significant promise by being intuitive, interactive, with a potential fast flow solver that provides near real-time feedback to the clinician.

I. Introduction

Upper airway surgery encompasses a group of procedures commonly used to treat upper airway obstruction, including maxillomandibular advancement, surgery of the soft palate, nasal surgery, tongue reduction surgery, and correction of tracheal stenosis. These procedures are used to treat common conditions associated with breathing difficulties,

including obstructive sleep apnea (OSA) and nasal airway obstruction (NAO). These conditions affect both children and adults.

Severe OSA affects up to 7% of adults and up to 10% of children [1], [2]. Poor patient adherence to treatment with continuous positive airway pressure (CPAP) is a significant problem leading to alternative treatment strategies, such as upper airway surgery [3]. However, the initial phase I surgeries show a success rate (50% improvement of symptoms) of only 50-60% [4].

Nasal airway obstruction (NAO) is a common health condition that affects about 9.5 million patients annually. Surgery is a preferred mode of treatment for predominant causes of NAO, such as deviated septum, hypertrophic turbinate, and nasal valve compromise. However, the longterm failure rates for NAO-related surgery tend to be high, ranging from 25% to 50% [5]. Examples of the pre- and post-surgery nasal passages for patients with upper airway obstruction can be seen in Figure 1.

Poor surgical outcomes can be linked to the current diagnosis and subsequent surgical decision-making process for these types of surgeries. There is a lack of dependable objective measures for determining which patients are candidates for surgery and the correct procedure for individual patients. There is a critical need to provide surgeons with reliable, patient-specific objective measures to (a) assist the surgeons in choosing appropriate surgical procedures, and (b) predict and quantify surgical outcome.

Developing a low-cost, easy-to-use tool that allows surgeons to perform this analysis with little assistance is key to improving surgical outcomes. A recent study has also shown the willingness of otolaryngologists to accept this type of tool [6]. However, previous efforts in the area have not produced an interactive surgical planning system with a fully functional end-to-end pipeline. This paper outlines the progress made in the development a comprehensive virtual surgery planning prototype for upper airway procedures. This includes the development of low-cost, intuitive segmentation and virtual surgery planning algorithms and computational fluid dynamics (CFD) evaluation of the virtual surgery solution. The quantitative assessment of the CFD analysis will determine whether the surgery provides a satisfactory clinical solution for the patient. If not, the virtual surgery can be modified to improve the results. The prototype was designed to provide virtual surgery planning tools for common NAO procedures: septoplasty, rhinoplasty, and turbinectomy. It primarily focuses on the preliminary components (model generation, interactive virtual surgery editing, and CFD analysis) of the system, shown in Figure 2.

II. Methods

A. Subjects

Ten patients from the Rhee study cohort were selected as described in [7], [8]. This cohort consists of patients recruited from the Ear, Nose, and Throat clinic at MCW who were at least 15 years old, had a clinical diagnosis of non-reversible, surgically treatable nasal obstruction (deviated septum, turbinate hypertrophy resistant to medical treatment, or lateral nasal wall collapse), elected to have surgery, and provided written, informed consent. This

study was approved by the Institutional Review Board at MCW. Axial computed tomography (CT) scans with pixel sizes of 0.303 or 0.313 mm and 0.6-mm thickness were obtained pre-operatively and 5 to 8 months post-operatively. To minimize nasal cycling effects on CFD results, only subjects with general symmetry in nasal mucus in both pre- and postsurgery scans were included in the original cohort.

B. Virtual Surgery Methodology

1) Model Generation: Segmentation—The 3DSlicer (www.slicer.org), open source platform was used to view and automatically segment the airways from the pre- and post-surgical CT scans. The user selects the entrance point to the nasal passages (nostril) on the sagittal view and the end of the region of interest (throat) on the axial view by placing one point in each location. The segmentation algorithm used is based on the algorithm by Hong, et al [9] and previously implemented in the Virtual Pediatric Airways Workbench (VPAW) [10]. A threshold value is automatically chosen based on the CT scan to separate the air from the anatomic head structure. A mask of the head is created using a morphologic closing operation. A second thresholding operation is performed on this region of interest to isolate the airways in the head. The segmentation is then trimmed based on the points originally selected to ensure no extraneous dead space is collected. This method was successfully used for pediatric airways in VPAW and the trim parameters were modified to better fit the adult airways in this study. These segmentations were compared to the previous segmentations developed in Mimics (<http://www.materialise.com/en/medical/software/mimics>), [7] and validated by subject matter experts.

2) Interactive Virtual Editing—The initial prototype focuses on two common procedures for improving air flow through the nasal passages: septoplasty, correction of a deviated septum, and turbinectomy, partial or complete resection of the inferior turbinate. The prototype provides a user-interface in the 3DSlicer application to allow the surgeon to identify the septum and/or turbinate and prescribe a geometric change.

Both the virtual septoplasty and turbinectomy procedures rely on interpolating a deformation field from a few user-specified seed points using thin-plate splines, as described in Sections *a) Septoplasty* and *b) Turbinectomy*.

a) Septoplasty: For septoplasty, “source” points for the deformation are placed along the current location of the septum, while an equal number of “target” points are placed along the desired post-surgery septum location. The differences between corresponding source and target points are used to drive the thin-plate spline interpolation [9]. Additional “anchor” points that represent structures that should not move can be placed on nearby anatomical structures to more tightly constrain the interpolated deformation.

b) Turbinectomy: The virtual turbinectomy requires only the placement of source points outlining the turbinate in a plane (typically a coronal CT slice). Target points for the deformation are computed automatically by fitting a circle to the source points in each slice and moving each source point toward the center of the circle. The distance to move toward the center varies based on the amount of turbinate reduction desired. The resulting

deformation is typically similar to a radially-symmetric shrinking of the turbinate radius. As with the septoplasty, anchor points can be used to more tightly constrain the deformation.

c) Usability Evaluation: Seven virtual surgery cases were completed for the prototype evaluation. These cases were then reviewed and minor adjustments were made in consultation with expert surgeon feedback. An informal feedback session was also conducted with our clinical expert to determine the usability of the virtual surgery module.

C. Computational Fluid Dynamics

The CFD analysis was performed using the Lattice Boltzmann Method (LBM) [11]. In recent years, this method has been implemented to model complex fluid flows as a more computationally efficient implementation of the Navier-Stokes equations. The LBM represents fluids as a collection of particles. The flow is calculated by directly advancing in time representative fluid particles taking into account collisions at a quasi-molecular scale. The system is modeled using the Boltzmann transport equation (1).

$$\frac{\partial f}{\partial t} + \vec{u} \cdot \nabla f = \Omega \quad (1)$$

where $f(\vec{x}, t)$ is the particle distribution function, $\vec{u}$ is the particle velocity, and Ω is the collision operator. This implementation confines the particles to a three-dimensional lattice with velocities oriented along the lattice directions. Previous work in this area has validated the use of the LBM for complex fluid flow analysis, including that with complex boundaries [12], [13], such as the upper airways [10].

Our implementation of the LBM leverages parallel processing techniques available with graphics processing units (GPU). The GPU LBM implementation (gLBM) was used to perform a rapid flow computation in the nasal passages. To verify the implementation, one of the original Mimics segmentations was analyzed with a pressure drop across the nasal passages as the boundary condition. The results of the LBM analysis were compared to the Fluent simulations from previous work [7], [8].

III. Results

A. Interactive Virtual Surgery Methodology

1) Model Generation - Segmentation—For each of the ten patients one pre- and one post-surgery segmentation were completed. Of the twenty, two failed to successfully segment the nasal passages. An example of the Mimics and 3DSlicer segmentations and an overlay comparison of the two is shown in Figure 3. The 3DSlicer segmentation provides a reasonable fit to the Mimics segmentations, but provides a more “rough” segmentation with the sinuses in place. The sinuses are a separate “region” of the segmentation; therefore, they do not affect the airflow and CFD calculations. The additional smoothing achieved in the Mimics segmentations is labor intensive and was required to allow the CFD mesh in Fluent to overlay the geometry and successfully compute the airflow, pressure, and heat flux. The LBM implementation does not require this additional smoothing to fit a grid structure of

particles to calculate the fluid flow. This allows a coarser segmentation to provide comparable CFD results, saving a significant amount of time and allowing for significant automation of the segmentation process. The semi-automatic 3DSlicer segmentation was generate in approximately two minutes, while the subject matter expertise driven segmentation in Mimics took hours to generate.

2) Interactive Virtual Editing

a) Qualitative Assessment: The virtual surgery outcomes, shown in Figure 4, were reviewed by an expert clinician. The overall assessment was that the software performed well in correctly aligning the septum. The general issues noted were with discontinuities in the airway and the ability to truncate or “shave” outgrowths or deformities that affect the symmetry of the airways. The discontinuities may be driven by mucus blockage in the airways or may be attributed to artifacts of the algorithm. With the additional segmentation editing tools available in 3DSlicer both of these issues were easily addressed to create virtual surgeries that well represent the post-surgery CT scans.

The most significant shortcoming noted by the expert clinician is the inability to reduce the width of the septum for each surgery. In many cases, it is necessary to “open” the airways by reducing the size of the tissue, cartilage, or bone to increase the available space for air to flow through the nasal passages. This is particularly true for correcting a lack of symmetry. This “shaving” operation is not well-addressed in the current virtual surgery system and will need to be addressed in future implementations.

b) Quantitative Assessment: To quantitatively asses the quality of our virtual surgeries, we placed landmarks along the midline of the septum in the pre-surgery CT scans and landmarks in corresponding positions in the post-surgery and virtual surgery scans. From these landmarks, we were able to compute the average distance from landmarks on the pre-surgery septum to the post-surgery septum and from the virtual surgery septum to the post-surgery septum.

Over seven cases, the average pre- to post-surgery distance was 1.2mm with a maximum of 4.75mm while the average virtual-surgery to post-surgery distance was 0.49mm with a maximum of 2.19mm, showing that virtual surgery on the pre-surgery CT is able to bring the septum significantly closer to its post-surgery state.

c) Usability Evaluation: The virtual surgery tool was evaluated by an expert clinician to provide usability feedback and assess the virtual surgery accuracy. The overall results were satisfactory and the final surgeries accurately closely matched the postsurgery CT scans. The virtual surgery results were quick to review and correct if unsatisfactory. However, the design of the interface requires a level of familiarity with 3DSlicer that is cumbersome for the casual user. Reviewing point selection, updating points, and using the segmentation editing tools to improve and modify the original virtual surgery requires changing modules in 3DSlicer. This requires navigating through multiple interface screens and understanding the array of menus available. This will be addressed in future versions by creating a single unified module that has all of the tools necessary to complete the virtual surgery.

The placement of the source, target, and anchor points was laborious. The number of points required for placement was not intuitive for the clinician. Anchor point placement was a particular challenge, because it relies on knowledge of the underlying algorithm which is unknown to the clinician. In future versions, this will be addressed by allowing the user to draw a line to highlight the septum, drawing a second “target” line for final septum location, and drawing a circle around the region of interest to “anchor” the shift and prevent inappropriate movement in surrounding tissue. We plan to explore the use of algorithms that would allow for automated changes of the patient’s septum and turbinate based on shape analysis of post-surgical CT scans. These approaches would greatly reduce the burden on the clinician and create a more viable tool for use in clinical practice.

B. Computational Fluid Dynamics

The segmented upper airway geometry was represented on a lattice with approximately a million voxels directly obtained from segmentation of a CT image. Though equally expensive when executed on standard computer architecture, LBM is more straightforward to parallelize than the full Navier-Stokes implementation. Therefore, when executed on modern GPUs, the computation time associated with gLBM is on the order of 15 minutes. Typically, the coarser geometry representation from direct voxelization of the CT images leads to local differences in the flow obtained by gLBM by comparison to that obtained on grids generated for Fluent. Nonetheless, the overall flow and cross-section average pressure drops obtained through gLBM compared well with those from Fluent, as shown in Figure 5. These preliminary results demonstrate that gLBM is a feasible alternative to Fluent for CFD analysis of the upper airway and will provide near real time feedback to the clinician and the viability of the surgery.

IV. Conclusion

An initial prototype of a virtual surgery planning tool for upper airway surgery has been successfully developed. Future work on this prototype will involve addressing the limitations exposed by our initial analysis and feedback.

We also plan to improve the CFD analysis by improving the GPU parallelization for additional computational efficiency. We will add secondary flow characteristics and temperature analysis to the gLBM to allow for heat flux analysis in the upper airways. Heat flux has been shown to be highly correlated to patient symptom relief [7].

While the initial prototype focuses on the surgeries associated with NAO, we plan to expand the use of the virtual surgery planning tool to include other upper airway surgery techniques. We also plan to validate the use for both pediatric and adult populations to provide the broadest translational focus possible.

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Figure 1.

A) CT scans and reconstructions of nasal airway obstruction pre- and post-surgery. B) Reconstruction of CT scans from pre- and post-surgery and surgical modeling for a stenosed trachea.

Figure 2. Interactive, patient-specific virtual surgery planning system, with the prototype components outlined in grey.

Figure 3.

Comparison for Mimics and 3DSlicer segmentations for both a pre- and post-surgical case show a qualitative fit.

Figure 4.

An example virtual septoplasty: A) the pre-operative CT image, B) the pre-operative CT with control points (current location in yellow, desired location in green, and anchor points in red), C) the virtual surgery result, and D) the post-operative CT of the patient.

Figure 5.

The gLBM implementation produces stable results that closely approximate the results produced in Fluent indicating a viable prototype for fast fluid calculations (pressure shown).