Preoperative Virtual Surgery to Optimize Nasal Airflow

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Introduction

Nasal airway obstruction is a common disease with high prevalence and significant social and economic burden. Nearly 9.5 million people annually present to their primary care physician with the chief complaint of nasal obstruction1 and nasal obstruction is responsible for an estimated $6 billion in annual healthcare expenditures2. Over 340,000 septoplasties and/or turbinate surgeries are performed annually for nasal airway obstruction, making this the 3rd most common set of procedures performed by otolaryngologists1. While septoplasty and/or turbinate surgeries are often successful in relieving nasal airway obstruction, between 10 - 40% of patients complain of persistent obstruction after surgery4,5,6. This moderate failure rate is in part due to traditional physical exam interpretations from anterior rhinoscopy correlating poorly to the patient’s sensation and probable 3D location of actual nasal obstruction. Furthermore, no objective measures of nasal airflow (such as acoustic rhinometry8, rhinomanometry9, etc) have been sufficiently accurate to be commonly used in clinical practice to aid the otolaryngologist in surgical planning. The development of an objective measure of obstructiveness that strongly predicted the location of anatomic nasal obstruction would be a great aid to improving the quality of nasal airway surgery and reducing the overall failure rate. In addition, this accurate objective measure could reduce the incidence of unnecessary surgery and help personalize and minimize operations for each unique patient. With the advances in computing processing speed in recent years, we have now come to use computational fluid dynamic analysis of 3D reconstructions of nasal airways from computed tomography images as a method for developing precise calculations of nasal airflow for individual patients. Furthermore, this approach also provides the added benefit of allowing the surgeon to perform pre-operative virtual surgery on the 3D reconstructions to optimize nasal airflow and create a personalized surgical plan for each particular patient. Here, we describe our collaborative efforts within the otolaryngology, biomedical engineering, and supercomputing disciplines to develop these software algorithms and the successful use of this approach with an actual patient with nasal obstruction.

Materials and Methods

3D models of the sinonasal cavities of the patient were reconstructed from sinus CT volumetric voxel data from the nasals anteriorly to the nasopharynx posteriorly. Images were taken on a 3D Acutome XYZ Slice View Tomograph (U. Morta MPG, Co). After the images were obtained, thresholding and segmentation were performed in a custom-programmed Matlab (Natick, MA) routine. The customized program allowed the surgeon to process each image (correlating to a computed tomography corona slice) individually or process images in blocks using the same parameter set. After the images were segmented, results were output in two different formats: 1) the domain was meshed, and the finite element mesh was used, and 2) a 3D stereolithography (STL) file of the reconstructed geometry was outputted. Due to the negligible effect on overall airflow resistance, the sinuses were removed from the computational domain10,11,12. A 3D reconstruction of the nasal airway was then created to allow the surgeon to interactively manipulate the anatomy of the nasal cavities. The surgeon could simulate a large variety of procedures, including: limited septalplasty, unilateral or bilateral submucous resection of the inferior turbinates, and concha bullosa excision of the middle turbinates. The virtual surgery is performed by allowing the surgeon to maneuver through the image stack, changing the region of interest on each subsequent image to either bone or tissue (black) or air (white).

Nasal airflow resistance plots

Airflow patterns in the nasal airways are governed by two main factors: nasal geometry and flow rate. As shown in previous literature, we assumed laminar flow models in our CFD flow model and associated quiet breathing (5 to 12 L/min) when performing CFD within the nasal passage13,14,15. Once the flow rate exceeds 20 L/min, as during light exercise or sniffing, nasal airflow becomes turbulent. In this study, only quiet breathing rates were considered, therefore, the flow was chosen to be modeled as incompressible and laminar. Also for this study, steady state inspiration was modeled.