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The effect of genioglossal advancement on airway flow using a computational flow dynamics model

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Abstract

Objective—Obstructive sleep apnea (OSA) is a sleep disorder caused by partial or complete collapse of the pharyngeal airway. Genioglossal advancement (GGA) is a well-tolerated surgical procedure intended to address hypopharyngeal collapse, yet there are few studies that monitor changes in airflow dynamics at this site. Computation fluid dynamics (CFD) utilizes airflow simulation to predict changes in airflow after anatomic manipulation.

Study design—We investigated the change in volume and airflow dynamics of the pharyngeal airway after GGA in a cadaveric model.

Methods—We performed serial GGA from 1mm (control) to 3mm, 7mm, and 9mm on a lightly preserved cadaver. After each intervention, we performed high-resolution computed tomography (CT) scans, reconstructed the pharyngeal airway, and quantified airspace volume and CFD analysis with both laminar and large eddy simulation (LES) models.

Results—Airway volume increased with linear GGA. In both CFD simulation models, velocity increased and pressure decreased after 9mm advancement secondary to increased airway diameter and less abrupt changes in airway geometry.

Conclusions—These results suggest that GGA may be effective in increasing airway volume and flow to address hypopharyngeal obstruction in OSA.

Keywords

obstructive sleep apnea; genioglossal advancement; computational flow dynamics

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Level of Evidence: N/A

Introduction

Obstructive sleep apnea (OSA) is a sleep-related breathing disorder caused by partial or complete collapse of the upper airway. Epidemiologic studies estimate that OSA affects 2 to 4 percent of middle-aged adults¹. While continuous positive airway pressure (CPAP) remains the gold-standard therapy for treatment of OSA, multi-level surgical therapies do play a role as second-line treatment of anatomical obstruction^{2,3}. Surgical interventions for OSA are designed to create permanent anatomic changes that relieve obstruction and improve airflow through the upper airway. Many of these treatments are unpredictable in effect, and their success often varies from patient to patient⁴. In particular, surgical methods targeted to address the retro-lingual airway and hypopharynx comprise a very heterogeneous group, and tend to be highly invasive with significant morbidity and relatively unpredictable results^{5,6}. Current surgical therapies for hypopharyngeal obstruction include: maxillomandibular advancement, genioglossus advancement, genioplasty, tongue radiofrequency treatment, surgical reduction of the tongue base (midline glossectomy), hyoepiglottoplasty, hyoid suspension, to name a few. Non-surgical treatments are also available, and include oral appliances and mandibular advancement devices^{7,8}.

Recognition of obstruction in the hypopharynx relies on information gathered from a thorough preoperative assessment that includes clinical examination, fiberoptic nasopharyngoscopy, and lateral cephalometric radiograph⁹. Despite the utility of these methods for diagnosis of hypopharyngeal obstruction, there is no reliable method to predict patient response to surgical therapy or to precisely quantify anatomic efficacy^{6,10–12}. This can complicate the issue of patient selection, which is of paramount importance when considering surgical intervention for OSA¹³.

Many have investigated the utility of computational fluid dynamics (CFD) for modeling airflow characteristics in the upper airway in OSA in order to allow for the prediction of changes in pharyngeal mechanics after anatomic and physiologic manipulations^{14–16}. This technique is ideal given the lack of suitable animal models and the poor feasibility of human experiments to simulate manipulations of airway anatomy. CFD has been used to examine the influence of various surgical interventions on airflow dynamics throughout the upper airway in OSA^{17–19}. To our knowledge, there has not been a study that has utilized CFD to analyze changes in airflow dynamics following genioglossal advancement (GGA).

Herein, we report the results of a cadaveric study of the effects of GGA on airflow dynamics throughout the upper airway. We simulated graded, serial GGA and utilized three-dimensional (3-D) airway reconstructions to calculate changes in airway volume, and CFD to analyze changes in airflow behavior in the airway.

Materials and Methods

Cadaveric model

We obtained a single lightly preserved (formaldehyde) cadaver. Although the cadaver was lightly preserved, the pharyngeal tissue was not compliant. We exposed the lower mandible using a vestibular incision and identified bilateral mental nerves. Bicortical cuts in an inverted “V” orientation were made through the mandible 5–6 mm inferior to the apices of the incisors. This was far enough inferior to maintain tooth vitality, but superior enough to maintain the muscular attachment to the genial tubercle on the lingual aspect of the mandible. This cut extended inferio-laterally to the inferior border of the mandible taking care to stay at least 5 mm anterior to the mental foramen so as to avoid damage to the inferior alveolar nerve. Once the cuts were complete, the free segment was advanced 1, 3, 5, and 9mm and bony contact verified. The segment was then secured in place with appropriate

plates and screws. After each advancement the cadaver was imaged using high-resolution CT. IRB approval was obtained for this study.

CT scans

CT data acquisition. Volumetric CT data sets were acquired with a 64 SOMATOM Sensation multidetector CT scanner (Siemens Medical Solutions). The following settings were used for scanning: 120-kVp X-ray source voltage, 250 mA / second effective current, and 0.75-mm slice thickness.

Pharyngeal volume

CT DICOM data sets were imported into the Amira visualization software platform (Mercury Computer Systems Inc.) for pharyngeal volume analysis. The pharyngeal volume was extracted, using Hounsfield units to select for airspace. The total number of voxels was then cumulated to give the digital pharyngeal volume.

CFD analysis

Two different models were used to simulate airflow changes in genioglossal advancement. For our preliminary data, we first utilized a laminar model of a commercial software ANSYS FLUENT® in which airflow was assumed to be streamlined without disruption, in order to obtain a preliminary idea of the flow feature with a cost-efficient manner. We set a velocity boundary condition at the inlet with air velocity of 1.5 m/s, and pressure boundary condition on the outlet. Because the geometry is complicated and Reynolds number (Re) is relatively high in the narrow passage, turbulent features are expected. Therefore, we adopted a large eddy simulation (LES) technique to correctly resolve complex flow features and compare the flow characteristics in two geometries of advancements of 1 mm and 9 mm. LES directly solves the filtered Navier-Stokes equations for grid-resolved scales and properly model the subgrid scale (SGS) flow characteristics. The in-house LES model (20) used in this study has been validated and used for complex airflow simulations in the human airways^{20,21}. We utilized normal breathing parameters with a tidal volume of 500ml, a period of 4.8 seconds to set a high flow rate of 342 ml/s at a peak inspiratory phase from a non-sinusoidal flow waveform and a low flow rate of 151 ml/s.

Results

Historically, cephalometric measurements performed before and after surgery have been used to document airway changes after hypopharyngeal surgery. Cephalometry is best at quantifying 2-dimensional changes in the anterior-posterior (A-P) diameter, but these changes underestimate the 3-D volume of airway expansion after genioglossal advancement (Fig 1A,B). In order to compare changes in linear advancement with 3-D volume, we calculated the hypopharyngeal volume after 3-D segmentation (Fig 2 A–D). As the genioglossal segment was advanced from 1 to 5mm, the hypopharyngeal volume increased in a linear fashion. As the segment was advanced from 5 to 9mm, the airway volume increased larger than expected (Fig 3). These changes are likely secondary to increases in both the anterior-posterior and lateral diameters of the airway, as it is “reshaped” with maximal advancement.

We used CFD to simulate how GGA would change airflow behavior. Due to computational time and cost, we analyzed differences in airflow at 1mm and 9mm advancements only. We first performed CFD using a laminar model, in which airflow is assumed to be streamlined without disruption. In this model we found that pressure drop along the pharynx decreased and velocity increased with genioglossal advancement, thereby increasing airway flow (Fig 4). Interestingly, due to the changes in hypopharyngeal shape after GGA advancement, CFD

airway simulations with the laminar model resulted in a large Reynolds number, suggesting turbulent airflow. To accurately quantify potential turbulent flow, we performed CFD large eddy simulation (LES).

In the LES model, preliminary simulation results show presence of turbulence with various intensities. With GGA, pressure decreases faster along the streamwise direction of the airway. SGS turbulent eddy viscosity is an indicator of presence of turbulent energy dissipation while the computational grid density is overall uniform in both meshes. SGS eddy viscosity overall decreased with GGA in both low flow rates (Fig 5) and high flow rates (data not shown).

Discussion

In this project, we examined the 3-D change in pharyngeal airway volume and flow after linear GGA. As the genioglossal segment was advanced, pharyngeal volume increased exponentially reinforcing the importance of analyzing airway data in three dimensions. We found that airway pressure decreased and velocity increased in the pharyngeal airway after GGA using a simplified laminar model of CFD. We utilized a LES model which replicated physiologic low and high flow rates of inspiration, and found similar decreases in airway pressure and decreased SGS turbulent eddy viscosity suggesting less turbulent airflow downstream. These findings suggest that GGA is effective in improving airflow in a cadaveric model of obstructive sleep apnea.

CFD to examine the effects of surgical manipulation on airflow dynamics in OSA is increasing in use. Recent studies have used this technique to evaluate various surgical interventions on airflow dynamics throughout the upper airway in OSA¹⁷⁻¹⁹. This has proven useful in light of the fact that there is no suitable animal model that is primed for study of this pathology, and human study for simulation of surgical intervention is not feasible. In light of these limitations, CFD has provided an excellent tool for study of the human airway that can be used to examine the influence of anatomic manipulations on the physiologic characteristics of the airway in OSA^{14-16, 22}.

Previous studies have also shown successful correlation of CFD results with clinical severity and potential application to treatment²³. CFD modeling has also been used to examine the influence of several surgical interventions on airflow dynamics of the upper airway in OSA¹⁷⁻¹⁹. To our knowledge, this represents the first study that has utilized 3-dimensional CFD to analyze changes in airflow dynamics following GGA.

In this study we utilized a cadaveric model, allowing us to perform multiple CT scans after graded GGA, which would not be possible in people due to ethical concerns. Additionally the high-resolution CT scans enabled us to perform detailed 3-D anatomical reconstructions and perform both laminar and LES CFD calculations. However there are several limitations with our study. The simulation of airway physiology during wake and sleep is complex, as the pharyngeal tissues consisting of muscle, fat, and mucosa exhibit different rates of compliance and rigidity during wake and sleep. We utilized a single lightly preserved (formaldehyde) cadaveric model. Although the skin and soft tissue were pliable, the pharyngeal region was not compliant. Therefore factors including airway collapse and compliance due to loss of tone of pharyngeal muscles could not be accounted for. These physiologic conditions could not be replicated in a cadaver model, and would require CFD to be performed in people while awake and asleep, a difficult proposition. We also investigated the effect of airway flow after genioglossal advancement. Although this allows us to isolate the effect to changes in the hypopharyngeal airway, genioglossal advancement is seldom performed as a stand-alone procedure. Genioglossal advancement achieves

horizontal unidirectional movement of the hypopharynx, while hypopharyngeal collapse may occur vertically or horizontally. Future studies will incorporate airflow changes in multi-level surgery in models as well as humans. CFD is a useful tool to examine airflow dynamics when it is well utilized, yet the cost and computing power of running studies limits its use. More in-depth analysis including additional simulations are needed to confirm the validity of its use in OSA. In summary, GGA increases the pharyngeal volume and decreases air pressure and turbulence in a cadaveric model of OSA.

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Figure 1. Cephalometric analysis for obstructive sleep apnea

Lateral cephalogram of person before (A) and after (B) 9mm genioglossal advancement. Black outline denotes skeletal landmarks, with blue outline denoting tooth position. White arrow highlights the anterior-posterior hypopharyngeal airway that is increased after GGA.

Figure 2. 3-D airway volume reconstructions

DICOM data from high-res CT scans were used to produce 3-D reconstructions after GGA. The airway was reconstructed (red) after 1mm (A), 3mm (B), 5mm (C), and 9mm (D) advancement.

Figure 3. Pharyngeal volume after GGA

Airway volume was calculated from 3-D airway reconstructions. As the genioglossal segment was advanced from 1 to 5mm, the hypopharyngeal volume increased in a linear fashion. As the segment was advanced from 5 to 9mm, the airway volume increased larger than expected.

Figure 4. Laminar flow CFD simulation

Airway pressure decreases along the pharynx and velocity increases from 1mm to 9mm advancement.

Figure 5. CFD Large Eddy simulation (LES) at low flow rates

In the low flow condition, airway pressure decreases and viscosity (airway turbulence) decreases from 1mm to 9mm advancement.