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Large Eddy Simulation of Flow in Realistic Human Upper Airways with Obstructive Sleep

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Abstract

Obstructive sleep apnea (OSA) is a common type of sleep disorder characterized by abnormal repetitive cessation in breathing during sleep caused by partial or complete narrowing of pharynx in the upper airway. The upper airway surgery is commonly performed for this disorder, however the success rate is limited because the lack of the thorough understanding of the primary mechanism associated with OSA. The computational fluid dynamics (CFD) simulation with Large Eddy Simulation (LES) approach is conducted to investigate two patient-specific upper airway flow with severe OSA. Both pre and post-surgical upper airway models are simulated to investigate the capability of CFD simulation for the prediction of the OSA surgery. Only the inhaled breathing is conducted with six periods (about 15 second) unsteady flow. Compared with the results before and after treatment, it is illustrated that there exists a significant pressure and shear stress dropping region near the soft palate before treatment; and after the treatment the flow resistance in the upper airway is decreased and the wall shear stress value is significantly reduced which means both surgery are successful. The analyze from the CFD is consistent with the parameters of clinical and LES can be a good tool for OSA study.

Keywords: OSA, CFD, Large eddy simulation, surgery

1 Introduction

Obstructive Sleep Apnea is a type of sleep disorder that is characterized by abnormal repetitive pauses in breathing or instances of abnormally low breathing during sleep in the upper airway (Figure 1), and it is usually associated with a reduction in blood oxygen de-saturation and sleep disruption. This disorder affects maximum 20% adults in the world and is increasingly recognized as an

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[‡] Created the 2D CT scans of the models in this document

[§] Created the 3D modeling and related mesh generation

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independent risk factor for a range of conditions including diabetes, hypertension and stroke (McCabe & Hardinge, 2011).

The short-term consequences of sleep apnea include sleep fragmentation, snoring, daytime sleepiness, and fatigue-related accidents. Without reasonable cure in the early stage of OSA, long-term adverse effects on cardiovascular functions may develop negative impacts on multiple organs and systems (Lipton & Gozal, 2003). Among the anatomical factors, airway narrowing, which may be caused by airway restriction or collapse, has been reported in both child and adult subjects with OSA. The morphological variation of narrowed upper airway could induce the airway to collapse. A better understanding of the unsteady flow field inside the airway, will allow us to characterize the airflow and pressure forces associated with airway narrowing in OSA patients (Mylavarapu, et al., 2009).



Figure 1: Major structure of upper airway.

Continuous positive airway pressure (CPAP) is the first choice for OSA treatment because of its non-invasive characteristic. However, the compliance of CPAP is a problem in some of the patients. So, surgery can be considered as the first-line treatment in OSA patients, for whom other non-invasive treatments failed. Surgical treatment of OSA aims to improve the size or tone of a patient's upper airway (Boudewyns & Van de Heyning, 2006). For decades, tracheostomy, including uvulopalatopharyngoplasty (UPPP), laser-assisted uvulopalatoplasty (LAUP) and Maxillomandibular advancement (MMA) etc., is the only effective treatment for sleep apnea and it is particularly effective for Asian people. However, the success rate of upper airway surgery is not good (Ito, et al., 2011; Iwasaki, et al., 2011; LI, et al., 2000). The post-operative complications after surgery are often the result of a dilemma during the operation of how much tissue to resect: too little is ineffective, yet too much may leave a patient with speech impedance and palatal stenosis, which can make OSA worse. Therefore, accurate prediction of tissue reduction for this treatment is urgently needed (Van Lierde, et al., 2002).

Due to the non-invasive nature, the Computational Fluid Dynamics (CFD) technique is used in this study to visualize the fluid flow in the upper airway. It can predict the fluid flow characteristics with static pressure, flow velocity, wall-shear stress etc. in the upper airway. It is believed that the CFD simulation is possible to predict the surgical outcome of the upper airway. However most of the studies in this field were based on the Reynolds-Average Navier-Stokes (RANS) solvers with two equation turbulence models, which have some limitations on the accuracy (Nithiarasu, et al., 2008; Yu, et al., 2006; Xu, et al., 2006; Mihaescu, et al., 2008; Jeong, et al., 2007; Powell, et al., 2011; Sung, et al., 2006; Zhao & Lieber, 1994). Therefore, a verified and validated Large Eddy Simulation (LES)

approach was employed to investigate the flow pattern in the severe OSA patients (Mihaescu, et al., 2011; Luo, et al., 2004).

This work utilizes LES with Sub-Grid-Scale (SGS) models to evaluate the surgery effect associated with OSA subject. Then the relationship between two OSA subjects results are analyzed to reveal the connection and evaluate the effectiveness of the operation. The airway models are reconstructed from cross-sectional computerized tomography (CT) imaging date. The static pressure and wall-shear stress in the upper airway for both subjects with pre- and post-treatment are addressed.

2 Methodology

2.1 Reconstruction of upper airway

Thoracic CT scans are taken from two Chinese male patients using a single-slice helical CT scanner (SS-CT). The images were obtained in the axial plane with a resolution of $0.7 \times 0.7 \text{ mm}^2$, and slice thickness is 0.625 mm. The three-Dimensional point cloud data of upper airway models were reconstructed using the image processing software Mimics (Figure 2).



Figure 2: The upper airway models: (a) subject #1-before surgery; (b) subject #1-after surgery; (c) subject #2-before surgery; (d) subject #2-after surgery.

2.2 Construction of the computational model

The mesh generator Gambit is used to reconstruct the airway geometry and to generate the mesh. The meshes near the wall are refined with the tetrahedral layer close to the wall surface to enhance the resolution in that region. The cell quantity in the computational model is about 3,400,000 for four models. A refined mesh has been employed near the larynx; these numbers are determined by using different meshes, from coarse to progressively finer meshes, and the numerical results of velocity are mesh-convergent to within a prescribed tolerance ($\sim 0.2\%$).

After meshing, the CFD software package Fluent (ANSYS 14.5) is used to solve the flow governing equations with finite volume method. Only the inspiratory process with tidal volume of 700ml is conducted with six periods (about 15second), and the inspiratory period is 2.5 s. The LES approach, which is a validated method for capturing transitional/turbulent unsteady, separated or vortical flows accuracy (Pope, 2000), is used to reveal such relevant flow features in the flow separation region located near the minimum cross-sectional area of the airway and the downstream region.

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In the LES modeling, the filtering operation for a variable (x) is provided by

$$\overline{\phi}(x) = \frac{1}{V} \int_{V} \phi(x') G(x, x') dx' \tag{1}$$

where V is the volume of a computational cell, and the filter function G(x, x') is defined as:

$$G(x,x') = \begin{cases} 1 & \text{for } x' \in V \\ 0 & \text{otherwise} \end{cases}$$
(2)

The filtering process effectively filters out eddies whose scales are smaller than the filter width or grid spacing. Thus the filtered Navier-Stokes equations are:

$$\nabla \cdot \overline{u} = 0 \tag{3}$$

$$\rho \frac{\partial u}{\partial t} + \rho \overline{u} \cdot \nabla \overline{u} = -\nabla \overline{P} + \mu_{eff} \nabla^2 \overline{u}$$
⁽⁴⁾

where \overline{u} is the filtered velocity, \overline{P} is the filtered pressure, t is time, and ρ is the fluid density. The $\mu_{\rm eff}$ is the effective viscosity which is unknown and will be modeled by sub-grid scale (SGS) model.

The flow governing equations are discretized on the computational domain using second-order finite-volume schemes and a second-order implicit scheme is employed for the time integration. The coupling between the pressure and velocity uses the scheme of SIMPLE. The Wall-Adaption Local Eddy-Viscosity (WALE) model is selected as the Subgrid-Scale model for returning the correct wall asymptotic behavior for wall bounded flows. The User-Defined inlet velocity is specified normal to the boundary plane (nostril) and the static pressure is set to be zero at the outlet (Luo & Liu, 2008). No-Slip boundary condition is imposed on all solid walls.

3 Results and Discussion

The numerical computation are mostly concerned with the pressure and wall shear stress distribution in the upper airway to evaluate the surgery effect for the airway collapse. Figure 3 and Figure 4 show the pressure distribution and wall shear stress distribution of subject #1 and #2 for both pre- and post-treatment. In both OSA subjects, the pressure shows similar distribution qualitatively associated with the airway shape. The static pressure at the minimum cross-section region (near retropalatal) for pre-treatment, decreases rapidly to a large negative pressure that is considered as the main factor induced the airway collapsed and caused the airway obstruction (Figure 3a, Figure 4a). While after surgery, the narrowed airway is widened and the pressure distribution changes into a much more uniform flow pattern, the negative pressure near retro-palatal became positive value. However, it still exists but moves to the downstream, near the posterior part of epiglottis tip in which section this negative region is not enough to cause airway collapse (Figure 3b, Figure4b).

Figure 3c and Figure 4c show the wall-shear stress distribution which also indicate the similar results at pre-treatment conditions. For both pre-surgery models the wall shear stress illustrates a sharp increase at the narrowed airway, indicating a significant velocity increasing which may induce a jetlike downstream flow, as shown in Figure 5. For the post-treatment models (Figure 3d and Figure 4d), the wall shear stress shows the same distribution characteristics for an obvious increasing at the epiglottis tip region with the disappearance of wall shear stress near soft palate.

Figure 5 shows the axial velocity contour and streamlines along a sagittal plane. It shows clearly that there is a jet flow for pre-surgery models. After surgery, the jet flow is attenuated for both subjects. There exists an obviously vortex downstream of the minimum cross-sectional area after the surgery that may active the mechanoreceptors then optimize the surgical effect (Liu, et al., 2012).



Figure 3: LES results of subject #1 during inspiration at peak flow rate: (a) instantaneous static-pressure distribution at pre-treatment condition; (b) instantaneous static-pressure distribution at post-treatment condition; (c) instantaneous wall shear stress distribution at pre-treatment condition; (d) instantaneous wall shear stress distribution at post-treatment condition.



Figure 4: LES results of subject #2 during inspiration at peak flow rate: (a) instantaneous static-pressure distribution at pre-treatment condition; (b) instantaneous static-pressure distribution at post-treatment condition; (c) instantaneous wall shear stress distribution at pre-treatment condition; (d) instantaneous wall shear stress distribution at post-treatment condition.



Figure 5: The axial velocity contour at peak flow rate time during inspiration along a sagittal plane: (a) instantaneous axial velocity distribution at pre-treatment condition for subject #1; (b) instantaneous axial velocity distribution at pre-treatment condition for subject #1; (c) instantaneous axial velocity distribution at pre-treatment condition for subject #2; (d) instantaneous axial velocity distribution at post-treatment condition for subject #2.

Samples	Before surgery		After surgery
Subject #1	69	15.8	
Subject #2	60.7	23.9	

Table 1: AHI measurement of OSA subjects.

Figure 6 and Figure 7 shows the variation of cross-sectional area at each cross-section for subject #1 and subject #2. For subject #1, as shown in Figure 6, the cross-sectional area at the minimum section is enlarged from 53.2 mm² to 111.1 mm², increased by two times. Meanwhile the AHI (Table 1) decreases from 64.8 (Severe OSA) to 15.8 (Mild), indicating an acceptable surgery outcome as can be seen from Table 1. For subject #2, as shown in Figure 6, the area is enlarged from 47.4 mm² to 235 mm², as about four times in area expansion. However, the reduction of the AHI from 60.7 (Severe) to 23.9 (Moderate) may suggest an unsatisfactory surgery outcome relative to the result of subject #1. Compared with the AHI after the surgery for both, it is concluded that the over-widened upper airway may not lower the AHI and get better treatment for the OSA patient.



Figure 6: The area of cross-section along the flow direction of subject #1 before(a) and after (b) surgery.



Figure 7: The area of cross-section along the flow direction of subject #2 before(a) and after(b) surgery.

4 Conclusions

The flow in CT-scan based OSA upper airways were simulated using CFD technique with LES turbulent modeling. Before treatment, the narrowed airway may induce significantly negative pressure

and large wall shear stress. Such negative pressure, if strong enough, can cause airway collapse, which is the most important factor for the obstruction in the airway. While large wall shear stress may eventually cause injury to the wall of upper airway. After surgery, the location of maximum static pressure and wall shear stress moves downward and the flow pattern becomes streamlined. All the pressure and wall shear stress values were significantly reduced in the whole upper airway of subject #2 while those of subject #1 did not change that much. This may indicate that the location where the largest aerodynamics forces distribution is also important. What worthy noting is that the over-widen may be worse for the condition of patients. The flow characteristics from simulation are consistent with the measurement of the surgery (mainly the AHI). From the simulation, we believe that the LES is able to capture the flow of OSA and predict the surgical outcome.

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