TURBULENT FLOW PATTERN IN UPPER AIRWAY WITH OBSTRUCTED SLEEP APNEA

M.Z. LU[1], Y. LIU[1,c], J.Y. YE[2]

[1]Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong
[2]Tongren Hospital, Capital Medical University, Beijing, China

[c]Corresponding author: Tel.: +85227667814; Fax: +85223654703; Email: mmyliu@polyu.edu.hk

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ABSTRACT: Computational fluid dynamics (CFD) techniques were used to model the turbulent flow in upper airway model of two subjects with obstructive sleep apnea (OSA). The upper airway models were reconstructed by Mimics software based on computerized tomography (CT) scanned images obtained during quiet tidal breathing. The Large Eddy Simulation (LES), a more accurate approach in unsteady flow, was selected to solve the unsteady flow. Only the inspiratory process was conducted with six periods (about 15second) and the mesh with the unstructured grid were generated from nostrils to trachea for both pre- and post-surgery models. From the numerical visualization, it can be seen that the pressure and shear stress drop rapidly from the choanae to the collapse region caused by area restriction, especially in the overlap region there exists a large negative pressure that induced the collapsing for OSA subjects before treatment. After surgical treatment, the distribution of airflow in the upper airway is more uniform. The results suggest the CFD techniques can show the turbulent flow pattern clearly and may help to evaluate the effect of the surgery.
KEYWORDS: OSA, upper airway, CFD, turbulence.

1. Introduction

Obstructive Sleep Apnea (OSA) is a type of sleep disorder that is characterized by abnormal repetitive pauses in breathing or instances of abnormally low breathing during sleep caused by partial or complete narrowing of the upper airway, and it is usually associated with a reduction in blood oxygen de-saturation and sleep disruption. This disorder affects more than 4% of male and 2% of female adults in the world and is increasingly recognised as an independent risk factor for a range of conditions including diabetes, hypertension and stroke [1-2].

The short-term consequences of sleep apnea include sleep fragmentation, snoring, daytime sleepiness, and fatigue-related accidents. Without seasonable cure in the early stage of OSA, long-term adverse effects on cardiovascular functions which may develop negative impacts on multiple organs and system [3]. 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 [4].

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 [5]. For decades, tracheostomy, including uvulopalatopharyngoplasty (UPPP), laser-assisted uvulopalatoplasty (LAUP) and Maxillomandibular advancement (MMA) etc., was 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 [6-8]. 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 [9].

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 [10-19]. 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 [10-17]. Therefore, a verified and validated Large Eddy Simulation (LES) approach was employed to investigate the flow pattern in the severe OSA patients [18-19].

This work utilizes LES with Sub-Grid-Scale (SGS) models to evaluate the surgery effect associated with two severe OSA subjects. The airway models were reconstructed from cross-sectional computerized tomography (CT) imaging date. The static pressure and wall shear stress in the upper airway for both pre- and post-treatment are addressed.

2. Methodology

2.1 Reconstruction of upper airway

Thoracic CT scans were 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 0.7×0.7 mm^2, and slice thickness is 0.625mm. The 3D point cloud data of upper airway models were reconstructed using the image processing software Mimics.

2.2 Construction of the computational model

The mesh generator Gambit is used to reconstruct the airway geometry and to generate the hybrid hexahedral/tetrahedral computational meshes which contains hexahedral cell in the interior of the domain and tetrahedral elements in the near wall regions. The meshes near the wall are refined with the tetrahedral layer close to the wall surface to enhance the solution in that region.

After meshing, the CFD software package Fluent (ANSYS 12.0) is used to solve the flow governing equations with finite volume method. Only the inspiratory process with peak inspiratory flow rate of 700ml/s for a period is conducted with six periods (about 15second). The LES approach, which is validated method [20] for capturing transitional/turbulent unsteady, separated or vortical flows accuracy, is used to reveal such relevant flow features in the flow separation region located near the minimum cross-sectional area of the airway and downstream of it.

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

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

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

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

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

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

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

where $\bar{u}$ is the filtered velocity, $\bar{P}$ is the filtered pressure, t is time, and ρ is the fluid density. The μ_{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 intergration. The coupling between the pressure and velocity is using the scheme of SIMPLE. The Wall-Adaption Local Eddy-Voscosity (WALE) model is selected as the Subgrid-Scale model for returning the correct wall asymptotic (y3) 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 [21]. No-Slip boundary condition is imposed on all solid walls.

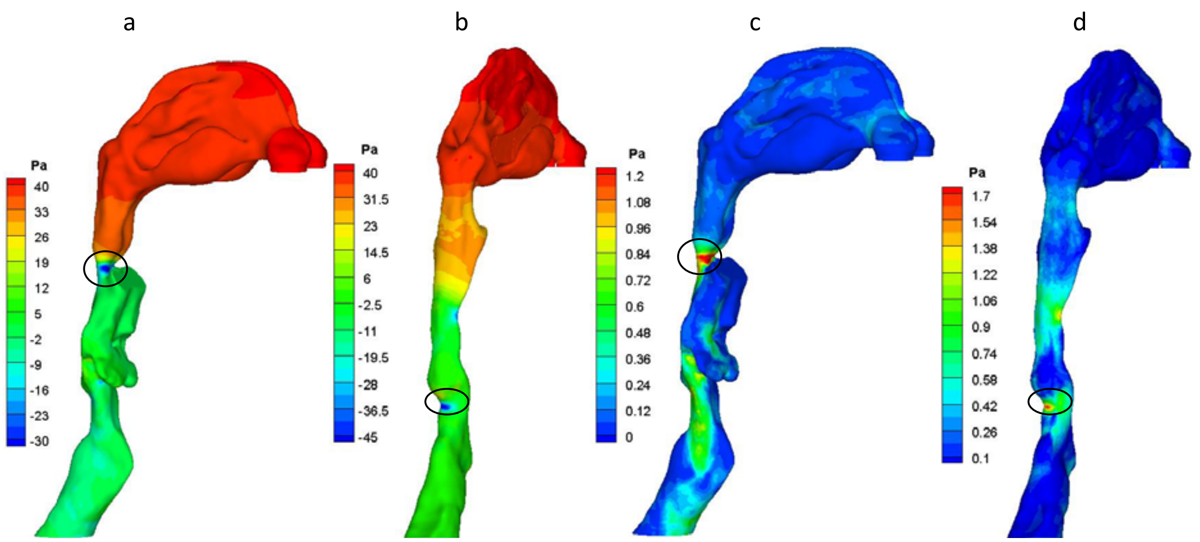

Fig. 1. LES results of subject #1 during inspiration at peak flow rate: (a) instantaneous static-pressure distribution at pre-treatment condition; (b) instantaneous static-pressure distribution at post-treatment condition; (c) instantaneous wall shear stress distribution at pre-treatment condition; (d)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

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. Fig. 1 and Fig. 2 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 retro-palatal) at pre-treatment conditions, decreases rapidly to a large negative pressure that may induce the airway collapse which causes the airway obstruction (Fig. 1a, Fig. 2a). While after surgery, the narrowed airway is widened and the pressure distribution changes into a much more uniform flow pattern. However, the negative pressure still exists but moves to the posterior part of epiglottis tip (Fig. 1b, Fig. 2b).

Fig. 1c and Fig. 2c show the wall shear stress distributions 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 increase which may induce a jet-like downstream flow, as shown in Fig. 3. For the post-treatment models (Fig. 1d and Fig. 2d), the wall shear stress shows the same distribution characteristic for an obvious increasing at the epiglottis tip region with the disappearance wall shear stress near soft palate.

It should be noted that the legend range is different for various subject models. The pressure and wall shear stress range of subject #2 decreased significantly after upper airway surgery. However, those of subject #1 did not change greatly.

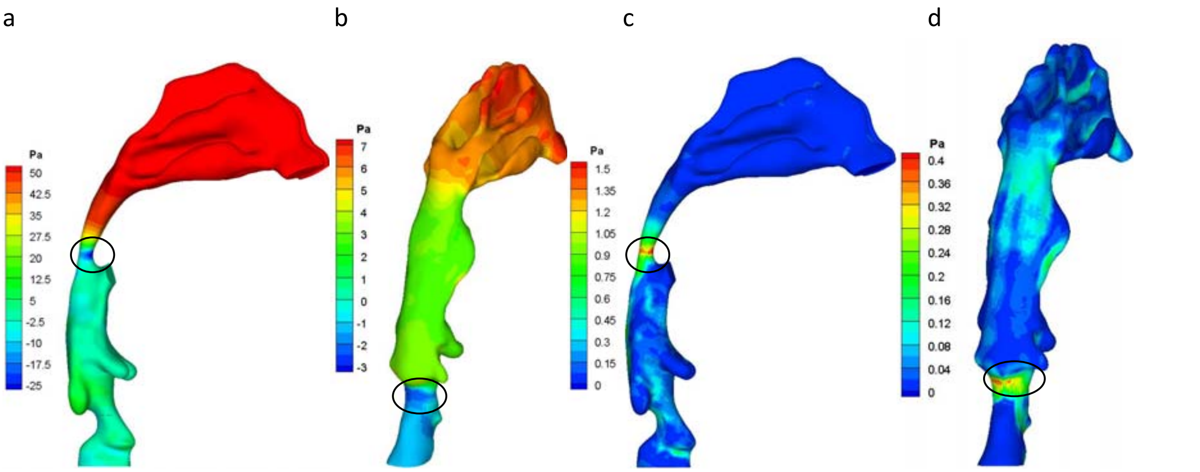

Fig. 2. LES results of subject #2 during inspiration at peak flow rate: (a) instantaneous static-pressure distribution at pre-treatment condition; (b) instantaneous static-pressure distribution at post-treatment condition; (c) instantaneous wall shear stress distribution at pre-treatment condition; (d)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

Fig. 3 shows the axial velocity contour in part of the upper airway. It shows clearly there exists a jet flow for pre-surgery model. After surgery, the jet flow is attenuated for both subjects.

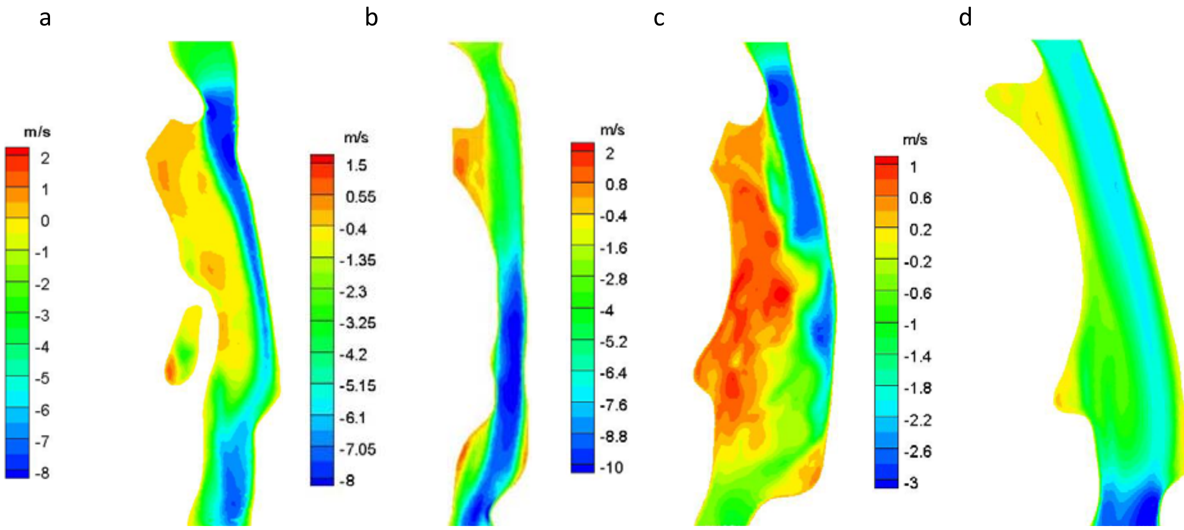

Fig. 3. LES results during inspiration at peak flow rate time: (a) instantaneous axial velocity distribution at pre-treatment condition for subject #1; (b) instantaneous axial velocity distribution at post-treatment condition for subject #1; (c) instantaneous axial velocity distribution at pre-treatment condition for subject #2; (d) instantaneous axial velocity distribution at post-treatment condition for subject #2.

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 significant negative pressure and large wall shear stress. Such nagative 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 significantly. This may indicate that the the location where the largest aerodynamics forces distribute is more important. From the simulation, we believe that the LES can provide much more details of the characteristics of the upper airway flow. By analyzing these flow variables, the effectiveness of the surgery can be evaluated qualitatively.

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