Computational Study on Obstructive Sleep Apnea Syndrome Using Patient – Specific Models

Y. Fan, L. K. Cheung, M. M. Chong, K. W. Chow, and C. H. Liu

Abstract—**Obstructive Sleep Apnea Syndrome (OSAS) is a common sleep disorder. It is characterized by repeated occlusion of upper airway and discontinuation of sleep. The breathing pauses and starts again with a loud snort. There may even be an abrupt interruption of sleep to maintain the patency of the airway. The pressure drop along the pharyngeal pathway should be a good indicator to show the severity of the pathological airways. Computational Fluid Dynamics (CFD) has become an important tool in investigating the internal flow dynamics of the respiratory system, especially for the upper airway. It provides a non–invasive environment for the analysis of the biological flow. Employing such technology, this study will provide insight for a male patient with severe OSAS. This patient also underwent surgical procedures to improve the size of the airway.**

The pre–operative and post–operative CT scans were reconstructed and converted to two patient–specific, three–dimensional models suitable for numerical simulations. The inhalation process was simulated using a constant volume flow rate, 0.3 liter per second (L s^{-1}), at the nostrils for both cases. An index, the 'resistance of the airway', was defined as the pressure drop per unit flow rate to estimate the tendency of airway collapse.

The pressure distribution from the velopharynx to hypopharynx was investigated. The pressure drops were 12.1 Pascal (Pa) and 7.3 Pascal before and after surgical treatment respectively. The resistance of airway changed from 40 Pa s L^{-1} to 24 Pa s L^{-1}, a 40% reduction.

The results showed that the pressure drop along the upper airway was reduced significantly after the surgical procedure. This decreased the collapsibility of the airway and consequently improved the sleep quality.

Index Terms—**computational fluid dynamics, obstructive sleep apnea, patient specific model, upper airway**

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I. Introduction

OBSTRUCTIVE Sleep Apnea Syndrome (OSAS) is a common sleep disorder breathing (SDB). It is characterized by repeated occlusion of the upper airway and discontinuation of sleep (Fig. 1). This leads to low respiratory rate (hypopnea) or suspension of breathing (apnea). The breathing pauses and starts again with a loud snort. There may even be an abrupt interruption of sleep to maintain the patency of the airway [1]–[6]. The poor quality of sleep highly affects the daily life and health conditions of the patients. OSAS leads to daytime sleepiness, loss of efficiency and motor vehicle accidents. It also increases the risk of stroke and death [2]–[4].

There is a serious and rapid increase in the incidence of the sleep disorder and related diseases. The prevalence of OSAS in Hong Kong is similar to that in the United States (4% in men, 2% in women) [5]–[6]. Obesity and craniofacial factors are two major contributed elements for OSAS. The Asian groups are relatively less likely to be overweight than their Caucasian counterparts. The craniofacial parts then become a bigger contributor to the development of OSAS in this predominantly Chinese population [1].

OSAS is a treatable form of sleep disorder breathing. The goals of treatments are to keep the airway open and to prevent pause of breathing during sleep. Continuous positive airway pressure (CPAP) is the first–line, non–invasive treatment for most patients [3]–[4]. For severe cases, invasive surgical procedures may be carried out. In our work, mandibular distraction was performed on a severe OSAS patient. The distraction is a method to increase the length of the lower jaw bone as well as the size of the pharyngeal airway.

The simulation technique employed here is computational fluid dynamics (CFD). It is a convenient and reliable tool for simulating the internal flow dynamics of the respiratory system [7]–[10]. CFD gives a prediction on the pressure distribution and other physical phenomena. We built patient–specific, three–dimensional models in order to analyze the dynamics inside the pharynx without *in vivo* experiments.

The main objective of this study is to analyze the pressure distribution and the airway resistance of a severe OSAS patient, before and after surgical procedure, by CFD.

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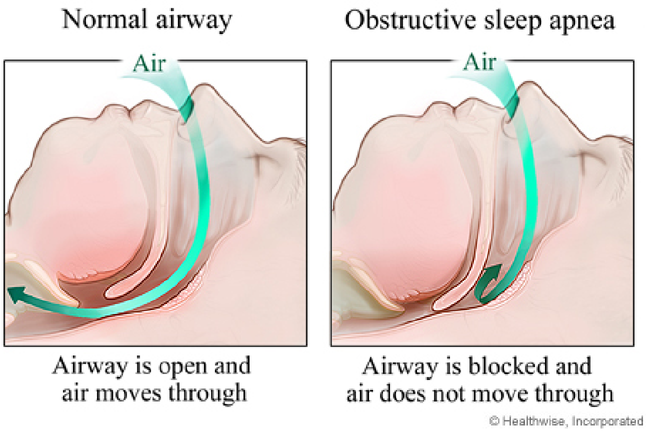


Fig. 1 The diagram shows the difference on the airflow between a normal airway and an obstructed airway.

II. Methods

High–resolution Computed Tomogram (CT) images were obtained for the construction of the patient–specific models. The mesh and mathematical models were treated by sophisticated commercial software. The flow patterns and streamlines were simulated by CFD. Subsequently, the pressure distribution could then be analyzed.

A. Patient Characteristics

The patient under consideration is a 45-year-old Chinese man. The body mass index (BMI) is 21 which can be classified as 'Normal'. He was diagnosed with severe Obstructive Sleep Apnea Syndrome, as well as severe mandibular hypoplasia due to condylar resorption, which means an unusually small size of the lower jaw. In order to improve the quality of sleep, the patient underwent a surgical intervention. The procedure included the intraoral distraction of the mandible.

B. Patient-Specific Modeling

The CT DICOM (Digital Imaging and Communications in Medicine) images were imported into commercial software (Mimics 13.0, Materialise, Belgium) for 3D reconstruction of the mathematical models. The models included the nostrils, the nasal cavity, the nasopharynx, velopharynx, and oropharynx and ended below the epiglottis (Fig. 2).

The reconstruction of the upper airway was based on the Hounsfield Units (HU) value, a measure of the electron density of the tissue, in the CT images. The HU value of air in the CT images ranged from -1000 to -500. The 3D models were then smoothed and meshed in 3–matic (Materialise, Belgium), and finally exported for further analysis (Fig. 3). Volume meshing was generated with reference to the surface mesh using the package TGrid 5.0.6 (ANSYS, Canonsburg, USA). High quality, unstructured grids were created. There were totally 1.5 x 10^6 cells in both pre–operation and post–operation models. Mesh independent test was taken.

C. Boundary Conditions

FLUENT 6.3.26 (ANSYS, Canonsburg, USA) was employed for the steady airflow simulation. The nostrils were defined as the location for velocity inlets, while the outlet boundary was situated just below the epiglottis. The velocities prescribed at the inlets were varied to match with the constant volume flow rate 0.3 L s^{-1}. The pressure was set to be zero at the outlet to mimic the normal breathing during inhalation. No–slip boundary conditions were applied on the walls of the airway.

The governing equations of fluid motion were the usual continuity equation (conservation of mass), and the Navier–Stokes (NS) equations (rate of change of momentum). In tensor notations (repeated indices implying summation), the continuity equation is

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

and the three dimensional NS equations are

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j}. \tag{2}$$

Where ρ = fluid density; u_i (i=1,2,3) = components of velocity vector; τ_{ij} = normal and shear stresses; p = pressure.

The flow in the upper airway was assumed to be incompressible and turbulent. The low Reynolds number k – ε turbulent model was applied for the simulations. In terms of material properties, the density of air was taken as 1.225 kg m^{-3}, and the viscosity was assumed to be 1.789 x 10^{-5} kg m^{-1} s^{-1}.

The focus of this study is on the pressure distribution along the pharynx. The computations would give a pressure difference (ΔP) for a flow rate (Q) inside the airway. The resistance of the airway (R) could then be determined using (3), using a reasoning similar to Ohm's law (resistance equals voltage divided by the current).

$$R = \frac{\Delta P}{Q} \tag{3}$$

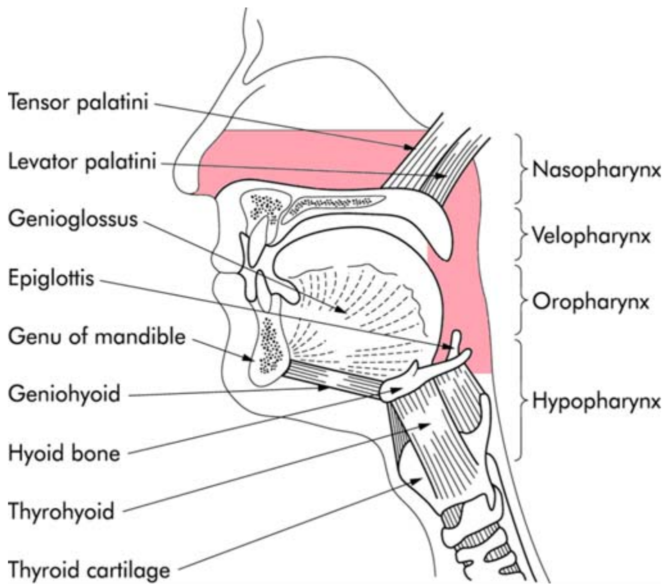
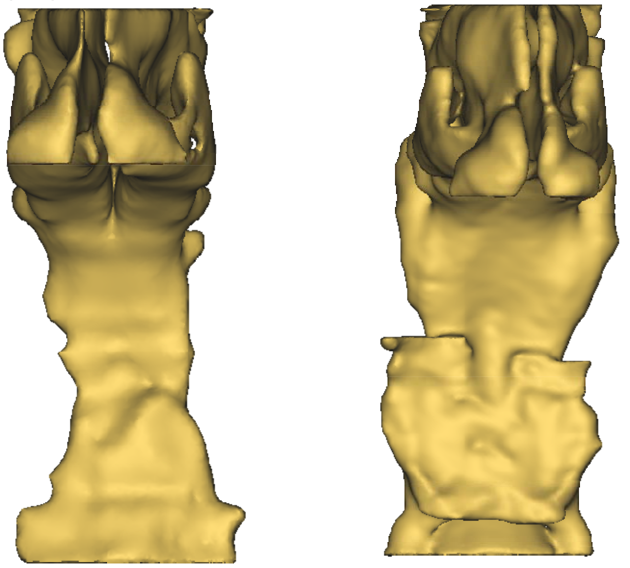


Fig.2 Anatomy of the upper airway. The part of interest is highlighted.



(a) (b)

Fig.3 The front view of the three–dimensional physiological models, (a) before surgical treatment, and (b) after surgical procedure.

III. Results

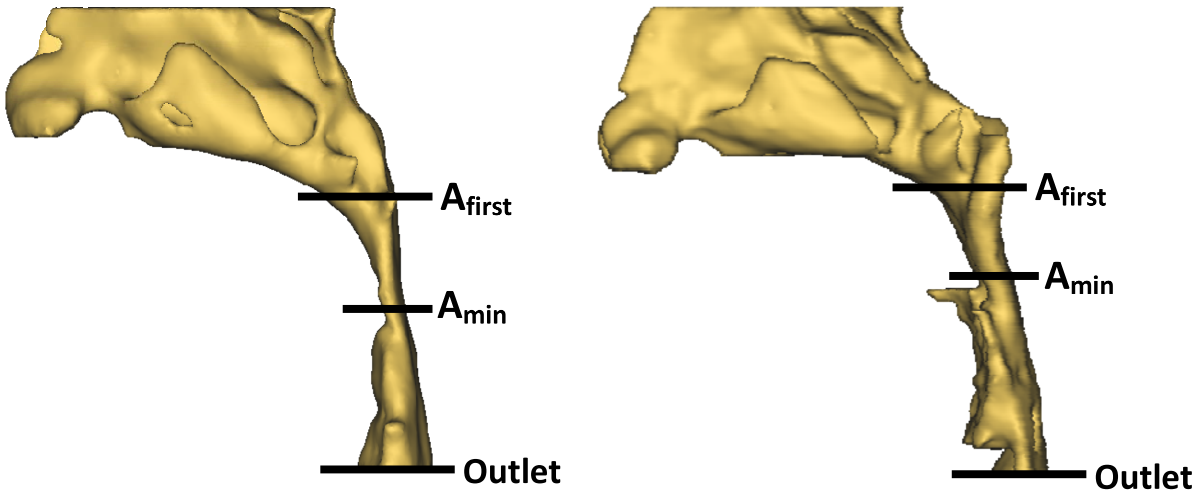
Two cases, the pre–operation and post–operation configurations, of a severe OSA patient were analyzed in this study. The main focus on the analysis was the region within the velopharynx (A_{first}) and the level of epiglottis (Outlet) (Fig 4). Twenty–one planes were defined along this portion in order to investigate the pressure variation at different locations. The first plane, A_{first}, was at the level of hard palate and the last plane was at the outlet, while the planes in between are equally spaced (Fig. 4).

From the reconstructed physiological models, we can easily see the differences in the sizes of the airway. Three–dimensional expansion was noticed in the pharynx which may give a better environment for breathing (Figs. 3 & 4). The percentage of stenosis of the upper airway was also studied. The plane with minimum area, A_{min}, was compared with the first plane, A_{first} (Fig. 4). The percentage of stenosis improved from 80.5% to 49.0% after the surgical treatment (Table I).

During inhalation, the atmospheric pressure was higher than the pressure in the lungs. The pressure drop drove the inflow of air. The pressure difference between the first and the twenty–first plane was 12.1 Pascal (Pa) before the mandibular distraction. After the surgery, the pressure drop became 7.3 Pa. With a constant volume flow rate, 0.3 L s^{-1}, the resistances were 40.2 Pa s L^{-1} and 24.3 Pa s L^{-1} before and after treatment respectively (Table I).

TABLE I
Comparison between Pre-operation and Post-operation

	A_{first} (cm^2)	A_{min} (cm^2)	Percentage of Stenosis	Resistance (Pa s L^{-1})
Pre–operation	3.3	0.6	80.5%	40.2
Post–operation	3.3	1.7	49.0%	24.3



(a) (b)

Fig. 4 The left view of the three–dimensional physiological models, (a) before surgical treatment, and (b) after surgical procedure. The definitions of A_{first}, A_{min}, and outlet.

IV. Discussion

Two main parameters were studied to investigate the effect of mandibular distraction. The minimum cross–sectional area in the upper airway increased threefold, from 0.6 cm^2 to 1.7 cm^2. The triple enlargement of the area caused a sharp drop in the percentage of stenosis. This widened airway highly reduced the chance of collapse and blockage during inspiration.

The airway resistance of the airway also dropped significantly, from 40.2 Pa s L^{-1} to 24.3 Pa s L^{-1}. This implied that the air could be breathed in more easily. The

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40% reduction in the resistance reduced the collapsibility of the pharyngeal airway. The quality of sleep would therefore be improved.

V. Conclusion

The pressure distribution and the resistance in the upper airway of the obstructive sleep apnea patient were studied using computational fluid dynamics. In order to mimic a physiological environment, three–dimensional patient–specific models were created using CT images of a severe OSAS patient.

The computational results showed a significant improvement in the breathing environment during inspiration after the distraction of the mandible. The 40% decrease in the airway resistance highly reduced the collapsibility of the pharyngeal airway.

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