RESEARCH ARTICLE

Establishment of upper respiratory tract model of patients with obstructive sleep apnoea hypopnoea syndrome before and after surgical treatment and its hydrodynamics analysis

Junjie Jin,[1] Zhonghua Tang,[2] Fan Zhao,[3] Ying Li[4]

Abstract

Objective: The study aimed to explore the method of constructing the upper respiratory tract model of patients with obstructive sleep apnoea hypopnoea syndrome (OSAHS) and its application in the detection of the changes of flow field characteristics of the upper respiratory tract before and after surgical treatment.

Methods: A 34-year-old male OSAHS patient was taken as the study subject. The improved Han-uvulopalato pharyngoplasty was adopted for treatment. A 3D model of the patient's upper respiratory tract was constructed based on CT scan results before and after surgery. The characteristics of upper respiratory tract flow field were analyzed based on computational hydrodynamics under unsteady respiratory conditions.

Results: A 3D model of the patient's upper respiratory tract was successfully constructed. And after the comparison, it was found that the patients' respiratory tract stenosis was significantly improved after surgical treatment. During inhalation and exhalation, the high pressure areas of the patient were located in the nasal vestibule and oropharynx respectively. Surgical treatment can significantly reduce maximum stress. The total pressure of the upper respiratory tract decreased by 16.9%, and the pressure of the nasopharynx and oropharynx decreased by 70.1% and 38.4%, respectively.

Conclusion: For the oropharyngeal area, the surgical treatment had obvious efficacy for inspiration, and during expiration, it had no efficacy but with adverse symptoms being increased.

Keywords: Upper respiratory airway, Obstructive sleep apnea hypopnea syndrome (OSAHS), Unsteady respiration, Flow field, Numerical simulation. (JPMA 70: 64 [Special Issue]; 2020)

Introduction

Sleep apnoea is a frequently encountered disorder. According to the epidemiological statistics, 60% of the middle aged and elderly people, and 20% adults suffer from sleep apnoea.[1] Obstructive sleep apnoea hypopnoea syndrome (OSAHS) is most harmful for the human body. It is characterized by repetitive narrowed upper airway or upper airway obstruction occurring during sleep, causing shallow or paused breathing. The world statistics show that each day around 3, 000 deaths are related to OSAHS.[2] The prevalence in Punjab in 2008 was 3~7%.[3] In terms of the middle-aged and the elderly people, the incidence of male people reached 24%, and the incidence of females was 9%.[4] Besides, the prevalence in children ranged from 1~10%. In China, the frequency of the middle-aged people is between 3.5~4.6%, of which there are approximately 70~80% middle-aged patients who are undiagnosed,[5] indicating that the confirmed diagnosis rate of the disease is very low.

In terms of the research of upper human respiratory system, the domestic and foreign scholars have done a lot of research work, but most were studied on simplified models such as tracheal-bronchial model, idealized oral-pharyngeal model and oral-pharyngeal-tracheal model.[6] There were also some research work[7] studied on the real Human upper respiratory tract, but that's far from enough, especially that there are few research on preoperative and postoperative OSAHS patients, therefore it's necessary to carry out an in-depth study on this. Targeted on OSAHS patients, this paper has proposed the real model of Upper respiratory tract, carried out the comparative analysis of anterior and posterior flow field and pressure, evaluated the surgical treatment efficacy and draw the relevant conclusions, which would be conducive to a deep understanding of the pathogenesis of respiratory disease, the clinical therapeutic effect and some factors that caused the breathing disorder. This research set up a real upper respiratory airway model, which adopted the unsteady

[1]School of Energy and Building Environmental Engineering, Henan University of Urban Construction, Pingdingshan, [2]School of Civil Engineering and Architecture, Southwest University of Science and Technology, Mianyang, [3]China Aerodynamics Research and Development Center, Mianyang, [4]Department of Otorhinolaryngology, Mianyang Central Hospital, Mianyang, China.

Correspondence: Junjie Jin. Email: 20141038@hncj.edu.cn

breathing boundary conditions and the standard turbulence model to conduct the simulated numerical computation of OSAHS patients before and after surgery.

Methods

In this research, the upper airway model was based on the upper airway of a 34-year-old male patient diagnosed with OSAHS, with the treatment operation being performed in modified Han-uvulopalato pharyngoplasty (H-UPPP). The patient was scanned by GE Lightspeed 16 slice spiral CT before and after the surgery, which adopted the spiral volume scanning. After the CT scanning, the 3-D reconstruction was performed with the related software, and the model was established as follows.

The expiratory volume or inspiratory volume chose the number of 750ml per time, with the respiration rate per minute of 20, and the respiratory cycle 3s, so the average expiratory volume or inspiratory volume per second was 500mL, with the mean respiratory volume being 30L/min. According to the air flow curve measured by Abbasi[8] nasal resistance meter, it was observed that the respiratory wave was approximately sinusoidal and the respiratory time ratio was approximately 1:1. Based on the unsteady respiration condition adopted in this experiment, the respiratory flow change could be processed according to the sinusoidal variation, which caused to the formation of the following formula:

(1) $Q = H \sin \omega t$

(2) $Qdt = 750$

(3) $= Q/A$

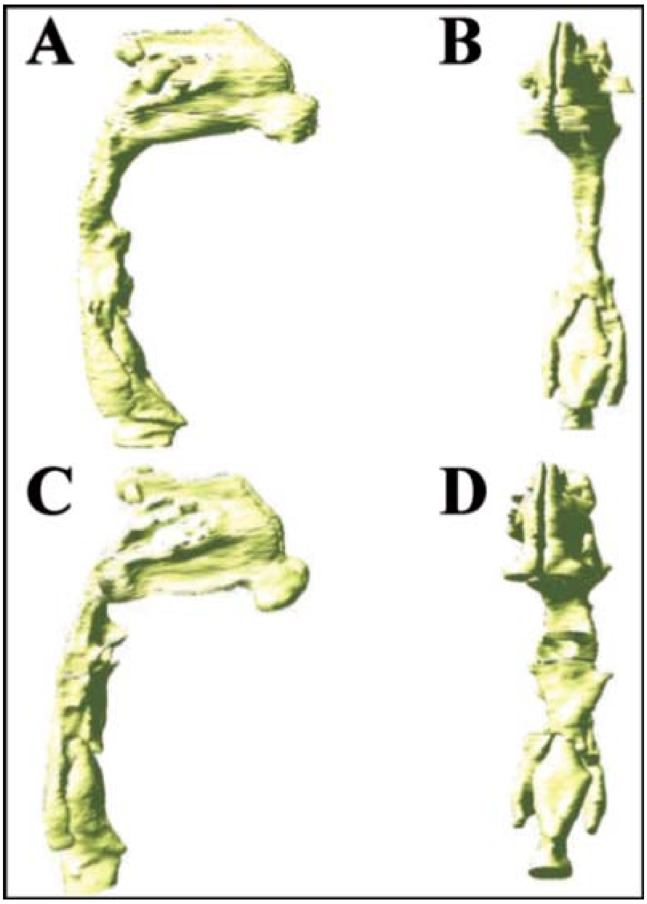
Where V is the inlet speed, A is the cross-sectional area of velocity inlet of underpart of glottis namely the laryngeal end, Q is the inspiratory volume or expiratory volume, H is a constant, ω is the angular frequency, and t is the time. As the respiratory cycle is 3s, thus $\omega=2\pi/3$, and according to the inspiratory volume or the expiratory volume is Q=750ml, so it can be obtained that $H=250\pi$ mL/s, then the laryngeal volume flow is $Q=250\pi\sin(2\pi/3)$ t mL/s.

Based on the computational fluid dynamics (CFD) method, a standard turbulence model was used for numerical simulation, and the boundary condition of the inlet was set in the position below the glottis. In the research, two extreme points of T1 and T2 namely the peak expiratory value and the peak inspiratory value were selected, and the corresponding gas flow of T1 and T2 moments was 785.4ml/s. This study adopted the unstructured grid. The grid number of the OSAHS patient before and after operation was 2,092,810 and 1,894,981 respectively, and the number of nodes was 400,354 and 365,106 respectively. According to the Grid precision analysis of Xiong,[9] the number of meshes reached 1,549,998, and the calculated results tended to be stable. Therefore, the mesh accuracy of the human upper airway model provided in this study was sufficient to meet the requirement of mesh accuracy.

Results

Figure-1 shows the use of 3D models of respiratory tract before and after surgery which were successfully constructed. Comparing Figure-A with Figure-C and Figure-B with Figure-C, it was seen that the stenosis of the respiratory tract significantly improved before and after surgery.

As shown in Figure-2A and Figure-2B, in the inspiratory state, the high pressure area was located in the nasal vestibule position both before or after surgery, and the



Note: figure A and figure B show the lateral view and elevation of the 3D model of respiratory tract before surgery. Figure C and figure D show the lateral view and elevation of the 3D model of respiratory tract after surgery

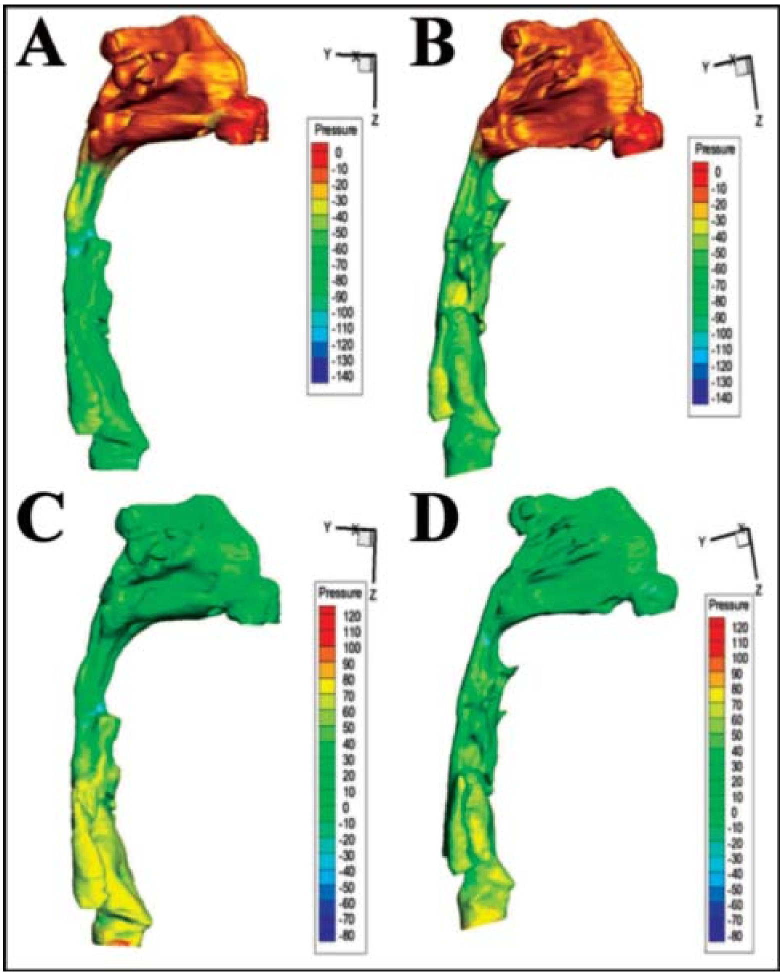
Figure-1: Lateral view and elevation view of 3D respiratory tract models before and after surgery.

Table-1: Before and after surgery of the various parts of the respiratory tract pressure drop and percentage.

Case	$\triangle p$ (Pa)	$\triangle p_m$ (Pa)	$\triangle p_n$ (Pa)	$\triangle p_h$ (Pa)	$\triangle p_w$ (Pa)
Before surgery	62.56	5.67	25.43	25.72	5.74
Percentage of total pressure drop	\	9.1?	40.6?	41.1?	9.2?
After surgery	51.98	15.49	7.61	15.85	13.03
Percentage of total pressure drop	\	29.8?	14.6?	30.5?	25.1?

Table-2: Before and after surgery of the various parts of the respiratory tract pressure drop and percentage.

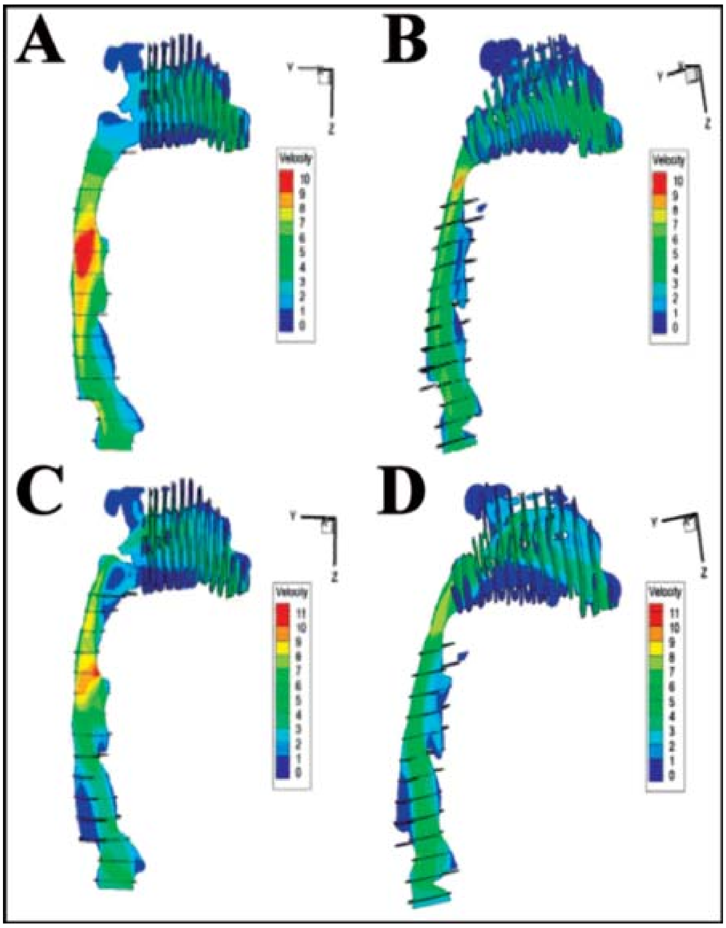
Case	$\triangle p$ (Pa)	$\triangle p_m$ (Pa)	$\triangle p_n$ (Pa)	$\triangle p_h$ (Pa)	$\triangle p_w$ (Pa)
Before surgery	62.47	5.69	17.18	25.03	14.57
Percentage of total pressure drop	\	9.1?	27.5?	40.1?	23.3?
After surgery	59.68	6.23	23.97	5.28	24.20
Percentage of total pressure drop	\	10.4?	40.2?	8.9?	40.5?



Note: figure A and figure B show the distribution of respiratory pressure before and after inhalation. Figure C and figure D show the distribution of respiratory tract pressure before and after exhalation

Figure-2: Distribution of respiratory tract pressure during inhalation and exhalation before and after surgery.

maximum value of both pre-operative and post-operative was close to 0, with little difference, but the minimum pressure of the patient had a clear difference with a preoperative value of -139.13Pa which was located in the narrow airway site namely the end of velopharyngeal area and the postoperative value was -113.42Pa at the end of nasopharynx. Before and after surgery, near the glottis and close to the posterior wall, there was a low pressure area, which was slightly lower than the minimum pressure area. It could be seen from the figure that there was a dividing line at the end of nasopharynx before and after surgery. The down part was located in a low pressure area while the upper part was located in a high pressure area. According to Figure-2C and Figure-2D, in the expiratory state, the maximum pressure before surgery was 138.98Pa, which appeared at the inlet of the respiratory airway namely the lower part of the glottis; the maximum pressure after surgery was only 100.49Pa-nearly 40Pa less than the original value, and it also appeared in the vicinity of the respiratory airway inlet. The vicinity of the whole respiratory airway inlet was in a high-pressure area similar to the pre-operative status. The maximum negative pressure zone before surgery was located at the end of the velopharyngeal area, with the maximal negative pressure being -88.53Pa. This was a narrow area of oropharynx, with the minimum pressure decreased to -44.45pa after surgery with half reduction to the original value of negative pressure. The postoperative low



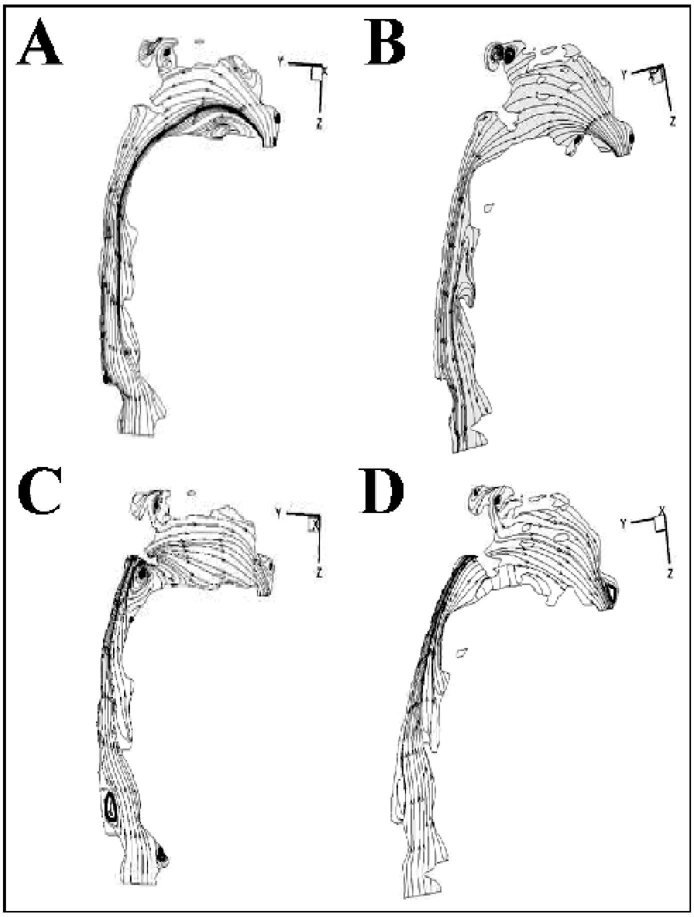
Note: figure A and figure B show the distribution of respiratory tract velocity before and after inhalation. Figure C and figure D show the distribution of respiratory tract velocity before and after exhalation

Figure-3: Respiratory tract velocity distribution during inhalation and exhalation before and after surgery.

pressure zone was transferred to the lower end of the nasopharynx and the airway at the end of velopharyngeal was no longer as narrow as it used to be.

As shown in Figure-3A and Figure-3B, when inhaling, it was observed that before surgery the high velocity area of the upper respiratory airway was concentrated in the oropharynx and the maximal rate of the upper respiratory airway was 10.98 m/s which was in the end of the velopharyngeal region. The high velocity flow at the site adjacent to the posterior wall of oropharynx had a negative effect on the wall, resulting in a relatively large impact force which could easily damage the tissue of the site. It was also to be noted that this site was also a negative pressure zone with a low negative value that would aggravate the collapse of the airway. This could be a negative effect and an important cause of the disease in OSAHS patients. After surgery, the high velocity flow was concentrated at the site close to the junction of nasopharynx and pharynx, with the maximum speed of 10.48m/s, which was 0.50m/s lower than the pre-operative state. As seen in Figure-3C and Figure-3D, when exhaling, the high velocity flow area of the whole upper respiratory airway was concentrated in the oropharynx region, and the maximum velocity of the upper respiratory airway was 11.55 m/s which was at the end of velopharyngeal region which was close to the front wall of the narrow site. The high velocity flow could result in a relatively large impact force causing damage to the tissue at the site. This along with the site being a negative pressure zone with a relatively high negative value, could aggravate the collapse of the airway. This was similar to the inspiratory state, which is an important cause of the disease in OSAHS patients. After surgery, the high velocity flow was concentrated in the lower middle part of the nasopharynx and the upper end of the velopharynx, with the maximum speed of 9.85m/s-which was 1.70m/s lower than that before surgery.

As seen in Figure-4A and Figure-4B, when inhaling, there were three different sizes of vortices that were formed at the upper end of the anterior nostril and at the posterior end of the olfactory cleft, especially the turbulence extent at the olfactory cleft was higher than that before the surgery. At the inferior turbinate anterior border, a back-flow phenomenon existed before surgery, but it developed into the vortex after surgery. Besides, the presence of back-flow occurred at the tip of the oropharynx after surgery was not shown before surgery. These phenomena were shown to be adverse effects to the fluid flow after surgery, aggravating the energy loss at the site Figures-4C and 4D show the exhaling pattern from the streamline before and after surgery. The vortex was seen in several positions before surgery, but they decreased in number after surgery and the streamlines appeared to be more evenly distributed. Before surgery, there were variant extent vortices in the glottis front, the back end of larynx and near the back wall, the airway of nasal septum end and the region near the end of the front wall of nasopharynx. But after surgery, these vortices were all gone and only the region near the posterior wall of the back end of larynx had a back-flow phenomenon, fully indicating the surgery had brought an obvious good effect.



Note: figure A and figure B show the distribution of respiratory tract streamline before and after inhalation. Figure C and figure D show the distribution of respiratory tract streamline before and after exhalation

Figure-4: Respiratory tract streamline during inhalation and exhalation before and after surgery.

Table-1 shows that the total pressure drop (△P) in the upper respiratory airway was reduced by 16.9% after surgery, whereas the pressure drop of the nasal cavity (△Pm) and the hypopharynx and the larynx (△Pw) slightly increased, while the pressure drops of the nasopharynx (△Pn) and the oropharynx (△Ph) were significantly decreased by 70.1% and 38.4% respectively compared to the preoperative values. The preoperative pressure drop was mainly concentrated in the nasopharynx and the oropharynx area, and the sum of the two accounted more than 80% of the total pressure drop. It can also be seen from the respiratory airway model that the respiratory airway at the lower end of the nasopharynx and the velopharyngeal area was relatively narrow, while after surgery the sum of pressure of the two parts dropped to 45.1%. As shown in Table-2, the total pressure drop (△P) in the upper respiratory airway was slightly reduced after surgery, and the state before surgery was the same as in the inspiratory state-the percentage of pressure drop in nasopharynx (△Pn) and oropharynx (△Ph) were still relatively large and the sum of the two was over 67%;after surgery. The nasal cavity pressure (△Pm) was slightly increased, and the pressure drop in hypopharynx and larynx (△Pw) were increased. As the pressure drop of the nasopharynx increased in the inspiratory state only, it indicated that the surgery had a beneficial effect. The expiratory state showed no improvement. However, it was seen that the oropharynx region largely improved due to the pressure drop, with a decrease of 78.9% from the original state.

Discussion

The most common cause of obstructive sleep apnoea hypopnoea syndrome is tonsil hypertrophy. The ethology is usually multifactorial, including hypotonia, tooth deformity, airway soft tissue hypertrophy and diseases of the nervous system. The treatment depends on the causative factors. Obstructive sleep apnoea hypopnoea syndrome is a common disorder. Research showed that the prevalence of OSAHS increases with age. Although the prevalence of OSAHS is very high, the diagnosis of OSAHS is still inadequate. A correct diagnosis requires the recognition of the symptoms. Functional symptoms, such as daytime sleepiness and cognitive impairment, are usually reported by people around the patient. The main treatment was continuous positive airway pressure. Because of the increased incidence of complications, the operation was not suitable.

This study reports the use of the unsteady breathing mode, which can more truly reflect the body's fluid flow in the upper respiratory airway. According to the research, the airflow in the upper respiratory tract of OSAHS patients was more stable after surgery, and the maximum breathing speed and minimum negative pressure were both lower than before the surgery. In addition, the total pressure of the upper respiratory tract was decreased, which was consistent with the results of Mylavarapu et al., Nowak et al., and Punjabi.[10-12] The titre in the oropharyngeal region of the patient decreased significantly after the operation, and the titre in the inhalation and exhalation decreased by 38.4% and 78.9%, respectively, indicating that the disease had been greatly relieved. In addition, the nasopharyngeal pressure decreased significantly during inspiration, but increased during exhalation, suggesting that the effect of this part of the operation improved during inspiration, but led to adverse effects during exhalation. Although the degree of decrease in respiratory pressure is not obvious, the comparison of the pressure profile in Figure-2 showed that the whole oropharyngeal high-speed flow area disappeared after surgery, and only a small area of high-speed flow[13,14] still existed. After surgery, the high-speed flow area below the upper pharynx disappeared, and there was obvious reflux phenomenon in the front of oropharynx, which indicated that the large area of high-speed flow area was greatly reduced through surgery, thus greatly reducing the disease of OSAHS patients.[15] By overall comparison, the upper part of the larynx and pharynx was in a relatively low-pressure area before and after the operation, while the lower part of the pharynx and the lower part of the pharynx were in a relatively high-pressure area.

However, comparing the speed of the pressure drop in the respiratory tract before and after the operation as shown in Figure-3, it was observed that the eddy current disappeared at the back of the larynx after the operation, which was necessary to alleviate the disease. The single vortex at the end of the olfactory fissure before surgery was replaced by two vortices after the operation. The vortices in the upper part of the anterior nostril prior to surgery were enlarged after surgery, indicating increased turbulence in both parts. In the exhalation state, the vortex was reduced and the streamline evenly distributed, which was favourable for the flow of the fluid. However, there are also studies that suggest that attention should be paid to the observation of the upper respiratory tract in OSAS patients. The purpose of this study was to investigate the relationship between the shape of upper airway and the severity of obstructive sleep apnoea syndrome (OSAS) during Müller's action. The study found that severe OSAS patients with upper airway lesions are more prominent. Obesity, NPC MCA, length of upper airway and mph may be related to the severity of OSAS. Obesity and gender should be considered when assessing upper respiratory anatomic abnormalities in snorers and OSAS patients.[16] In addition, some studies have found that the decrease of airway volume does not depict the type of respiratory events, but there is a significant narrowing of velopharyngeal closure in both dimensions, so the occurrence of the narrowest value below a certain level will lead to more apnoea.[17]

Obstructive sleep apnoea hypopnoea syndrome is characterized by repeated reduction of airflow due to collapse of the upper respiratory tract during sleep. OSAHS involves repeated collapse of the sleep related upper respiratory tract (UA). The mechanical properties and neural control of UA were changed to apply mechanical load to the inspiratory air. UA collapse does not occur during wakefulness and therefore relies on compensation for wakefulness. The experimental inspiratory load of normal subjects caused respiratory related cortical activity. It was concluded that the outcome of treatment could not be determined simply by examining the streamline profile, but a profound understanding of the characteristics of the fluid flow in the respiratory tract was required. After surgery, the narrow part of the pharyngeal cavity cross-sectional area was changed to 2.3 times to the original, and the laryngopharynx part also got large changes after surgery. Therefore, it was concluded that resection surgery of one part not only changed the structure of that part, but also affected the structure deformity of other parts of the respiratory tract. The integrated assessment is essential to determine the impact of surgery on the deformity.

Conclusion

In this study, it was found that CT scan combined with 3D modelling can effectively construct the 3D model of the upper respiratory tract of OSAHS patients. After hydrodynamics calculation of the 3D model of the patient's upper respiratory tract, it was found that the main lesion site of OSAHS patients was oropharynx. Especially pharyngeal stenosis caused more damage to the airway wall. However, H-UPPP surgical treatment can reduce the flow speed and pressure in the high-speed flow area in the high-pressure or low-pressure area of the respiratory tract of OSAHS patients, thus reducing the stenosis degree of the respiratory tract. However, it is still necessary to carry out further research on the pathogenesis of OSAHS patients and the structural deformation and the advantage of surgical treatment.

Disclaimer: I hereby declare that this research paper is my own and autonomous work. All sources and aids used have been indicated as such. All texts either quoted directly or paraphrased have been indicated by in-text citations. Full bibliographic details are given in the reference list which also contains internet sources. This work has not been submitted to any other journal for consideration.

Conflict of Interest: We declare that all contributing authors of this paper has no conflict of interest and all have contributed equally for this research work.

Funding Disclosure: This work was supported by contributing authors University through internal research grant.

References

1. Baldwin CM, Ervin AM, Mays MZ, Robbins J, Shafazand S,

Walsleben J, et al. Sleep disturbances, quality of life, and ethnicity: the Sleep Heart Health Study. J Clin Sleep Med 2010;6:176-83.
2. Hoffstein V, Mateika JH, Mateika S. Snoring and sleep architecture. Am Rev Respir Dis 1991;143:92-6. doi: 10.1164/ajrccm/143.1.92.
3. Qamar A, Ali SI, Ghuman F, Owais M, Ahmed R. Effects of obstructive sleep apnoea on lipid metabolism: a cross sectional study from a tertiary care hospital of Pakistan. Pak J Physiol 2017;13:7-10.
4. Julien JY, Martin JG, Ernst P, Olivenstein R, Hamid Q, Lemière C, et al. Prevalence of obstructive sleep apnea-hypopnea in severe versus moderate asthma. J Allergy Clin Immunol 2009;124:371-6. doi: 10.1016/j.jaci.2009.05.016.
5. Shareef M, Khaliq T, Faisal MN, Majeed W, Shahid M, Jamal M, et al. Comparative Anti-Bacterial Activities Of Nigella Sativa And Lincomycin In The Gut Of Broiler Chicks. Matrix Sci Pharma 2017;1:6-12. DOI: 10.26480/msp.02.2017.06.12
6. Fahim NF, Sultana Z. Assesment of Hepatoprotective Activity of Roots and Barks of Achyranthes aspera in CarbonTetrachloride-Induced Hepatotoxicity in Rats. Malays J Halal Res 2018;1:23-6. DOI: 10.26480/mjhr.02.2018.23.26
7. Al Islam S, Javaid Z, Ghaffar A, Jamil Y. The Effect Of Salt Concentration On Absorbance And Conductance Of Fricke Dosimeter. Acta Chem Malay 2018;2:15-22. DOI: 10.26480/acmy.02.2018.15.22
8. Abbasi M, Rafique U, Murtaza G, Ashraf MA. Synthesis, characterisation and photocatalytic performance of ZnS coupled Ag2S nanoparticles: A remediation model for environmental pollutants. Arab J Chem 2018;11:827-37. Doi: 10.1016/j.arabjc.2017.12.017
9. Xiong J, Sun Z, Yu S, Xu H, Wang S, Ashraf MA. Preparation and properties of sugarcane bagasse cellulose biofilm carrier. Pap Asia Compendium 2018;2:20-6.
10. Mylavarapu G, Murugappan S, Mihaescu M, Kalra M, Khosla S, Gutmark E. Validation of computational fluid dynamics methodology used for human upper airway flow simulations. J Biomech 2009;42:1553-9. doi: 10.1016/j.jbiomech.2009.03.035.
11. Nowak N, Kakade PP, Annapragada AV. Computational fluid dynamics simulation of airflow and aerosol deposition in human lungs. Ann Biomed Eng 2003;31:374-90. doi: 10.1114/1.1560632.
12. Punjabi NM. The epidemiology of adult obstructive sleep apnea. Proc Am Thorac Soc 2008;5:136-43. doi: 10.1513/pats.200709-155MG.
13. Xu C, Sin S, McDonough JM, Udupa JK, Guez A, Arens R, et al. Computational fluid dynamics modeling of the upper airway of children with obstructive sleep apnea syndrome in steady flow. J Biomech 2006;39:2043-54. doi: 10.1016/j.jbiomech.2005.06.021.
14. Ye JY, Wang XY, Han DM, Gao LM. Epidemic survey of the middle and aged women related obstructive sleep apnea hypopnea syndrome in Beijing. Zhonghua Er Bi Yan Hou Tou Jing Wai Ke Za Zhi 2005;40:611-7.
15. Zhang Z, Kleinstreuer C, Kim CS. Gas-solid two-phase flow in a triple bifurcation lung airway model. Int J Multiph Flow 2002;28:1021-46. Doi: 10.1016/S0301-9322(02)00011-3
16. Huang JF, Chen GP, Wang BY, Xie HS, Zhao JM, Wu LH, et al. Assessment of Upper-Airway Configuration in Obstructive Sleep Apnea Syndrome With Computed Tomography Imaging During Müller Maneuver. Respir Care 2016;61:1651-58. doi: 10.4187/respcare.04669.
17. Özer T, Selcuk A, Yilmaz Z, Voyvoda N, Cam, Özel HE, et al. The role of upper airway morphology in apnea versus hypopnea predominant obstructive sleep apnea patients: an exploratory study. Br J Radiol 2018;91:e20170322. doi: 10.1259/bjr.20170322.