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Computational Fluid Dynamic Study of the Pharyngeal Airway Characteristics Before and After Mandibular Setback Surgery in Patients with Mandibular Prognathism

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ABSTRACT

Mandibular prognathism had been one of the most inconvenienced deformities developed in humans. This type of deformity possesses a protruded mandible jaw, and it can cause inconvenience in talking chewing and affect the aesthetic of the person diagnosed with this problem. However, this problem can be solved through mandibular setback surgery. This surgery will reposition the mandible jaw backward. The main concern of this surgery is, by repositioning the mandible jaw backward, the cross-sectional area of the airway will also be reduced. This condition might induce the iatrogenic of Obstructive Sleep Apnea (OSA). Thus, this study analyzed the characteristic of the pharyngeal airway in pre-treatment and post-virtual-operative conditions. This analysis simulates the pharyngeal airway with the Computational Fluid Dynamic (CFD) method. The respondent's data was obtained from computed tomography (CT) scan and was modeled into a 3-dimensional (3D) model. The simulation process takes place using the 3D model, mesh generation, and boundary conditions set-up. The flow pattern, pressure drop, airway wall shear stress, and turbulent kinetic energy were compared between both simulations. The simulations result present that, after the surgery, the pharyngeal airway decreases significantly. The pressure drop, flow pattern, airway wall shear stress (WSS), and turbulent kinetic energy (TKE) seem more significant around the critical plane in the post-treatment condition. However, these factors did not contribute to the OSA as it is not large enough to become the cause of OSA.

1. Introduction

The upper airways of humans are significant in daily life [1]. An upper airway, also known as the upper respiratory tract, provides air to breathe in and out from the lungs. Besides, it also provides air warming, humidification, pathways for olfaction, and filters the air coming in and out of the lungs. The upper airway consists of the nose, nasal cavity, nasopharynx, oropharynx, laryngopharynx, and extrathoracic part of the trachea. During sleep, in typical cases, the upper airway muscle activity is being reduced [2].

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In some cases, obstruction might develop in the upper airway. Obstruction is when the muscle in the back of the throat relaxes too much, causing the airway to narrow or close. This condition will lead to inadequate breathing [3]. Prognathism is a case where it involves the structure of the base skeleton of the patient diagnosed with prognathism. There are three types of prognathism: mandibular prognathism, where the lower jaw becomes protruding; maxillary prognathism, where the upper jaw protrudes; and bimaxillary prognathism, where both upper and lower jaws are sticking out. Mandibular prognathism is also known as Habsburg jaw, extended chin, or skeletal class III malocclusion. The skeletal class III malocclusion may cause difficulty talking, chewing, and biting and contribute to significant airway obstruction. Besides, it also may cause difficulty in tracheal intubation when needed [4].

In order to overpower this deformity, a mandibular prognathism surgery was done to relocate the protruding jaw. The extended base skeletal was being setback to alter the alignment of the teeth. However, the setback of mandibular prognathism surgery will cause a reduction in oropharyngeal airway dimensions, which might cause sleep-disordered breathing. Sleep disorder breathing, or obstructive, can be classified into two cases: obstructive apnea, where the airway is fully obstructed, and obstructive hypopnea, where the airway is partially obstructed. In this case of mandibular setback surgery, previous research had stated that there were possibilities that the patient was diagnosed with Obstructive Sleep Apnea (OSA) after the post-surgery.

Patients diagnosed with Obstructive Sleep Apnea (OSA) might experience choking, gasping, or snoring during their sleep [5, 6]. OSA will repeatedly cause the breathing to stop and start during sleep. The obstruction in the upper airway was produced by the tongue retracting into a position with the posterior of the pharyngeal wall. The muscles which are the support structure, including the soft palate and uvula in the back of the throat, relax too much and result in the narrow or close of the airway. During this time, breathing may be inadequate. Consequently, a vibration of soft tissues and snoring produced during sleep caused damage to the soft tissue, vessel, and nerves.

As the airflow happens in the upper airway, the Computational Fluid Dynamics (CFD) has been used as a tool to get an insight into this disease and many applications [7-11]. CFD tool has emerged from observing OSA type of disorder and can help other medical disorders. In this case, by using CFD tools, a simulation can be utilized to visualize better the actual condition of the OSA patient's upper airway and help to get a better understanding. A computational simulation is essential in understanding the upper airway flow in obstructive sleep disorder. This CFD simulation can help in a better finding of clinical practices. Therefore, in the current study, the investigation of the flow characteristic for patient mandibular prognathism surgery before and after mandibular setback was being set as the aim of the study.

2. Subject and Method

2.1 Reconstruction of Airway Geometry and Meshing

The data of the respondent was obtained from a CT scan. The respondent had a history of suffering mandibular prognathism deformity. The respondent then did a mandibular setback surgery to setback the protruding mandible. The pre-treatment and post-treatment data CT scan was stored in Digital Imaging and Communications in Medicine (DICOM) format [8]. The data were then transferred into Mimics Research software to perform image segmentation and create a three-dimensional trigonal surface model. In this case, the nasal cavity was being excluded in the modeling of the surface model. The nasal cavity generates complex turbulent flow patterns upstream of the pharynx. The airway surface model was created based on the DICOM image series's pixels' info (Hounsfield units). The data from Mimics Research software were transferred into 3-Matic Research software to create a volume mesh of the pharyngeal airway. Then, generation of mesh will be conducted using pre-processor ICEM software.

In this study, unstructured tetrahedral meshes were generated with a 1.3 million-mesh size—the grid independence study and the solver validation were already done in previous research. The mesh type provides acceptable accuracy in analyzing the pharyngeal airway [12, 13]. The mesh quality is essential in a simulation process involving CFD because the meshes will affect the result of the simulation. Thus, this type and size of the mesh are chosen based on the sensitivity grid test done with different grid sizes. The mesh convergence test was done using pre-processor ICEM (ANSYS, United States).

2.2 Governing Equation

The governing equation in this simulation process is the continuity Eq. (1) and momentum Eq. (2), which describe and solve the incompressible flow of the fluid in the upper airway. These equations will calculate the velocity and the pressure of the flow. Due to the small contribution regarding the effect of change in temperature upon the airway in this study, the energy equation was neglected.

$$\nabla \vec{v} = 0 \tag{1}$$

$$\rho(\vec{v}.\nabla)\vec{v} = \rho\vec{g} - \nabla p + \mu\nabla^2\vec{v} \tag{2}$$

where $\vec{v}$ is the velocity vector, p is the air pressure, $\overrightarrow{g}$ is the gravity vector, ρ is the density of air and μ is the viscosity of air.

The data is being solved by using these equations with ANSYS 16.0 software. The simulation was done in this study by computing the flow field using a steady-state Reynolds averaged Navier– Stokes (RANS) formulation with the k–ω shear stress transport (SST) turbulence.

2.3 Boundary Conditions

The cross-section of the nasopharynx was defined as the inlet boundary, and the vocal cord was defined as the outlet boundary of the CFD model. A maximum volume flow rate of 42L/min (700ml/s) [14] was defined according to the average air volume flow rate at the inlet. The viscosity and density of fluid of 1.7894 x 10^{-5} Pa.s and 1.225 kg/m^3, respectively, had been defined as the boundary condition. The velocity imposed at the air wall is defined as a no-slip condition

3. Result and Discussion

3.1 Area

The respondent's pharyngeal airway starts with the cross-section of the nasopharynx as the inlet and vocal cord as the outlet is being observed. The cross-sectional area along the pharyngeal airway is being analyzed. Figure 1 portrays the planes being created for both types of conditions. The figure shows that the airway length being analyzed in this study for both the pre-treatment and post-treatment conditions is not the same. Therefore, it is being created for both types of conditions. Due to the difference in the length of both airway types, it has been decided that only nineteen planes are being created. This ensures that the planes created are at a uniform distance for both conditions. Hence, a comparison can be made between the planes for both types of conditions. The pharyngeal airway flow was segmented horizontally into the nineteen planes, with every plane 2.5 mm apart.

The plane was being created to avoid confusion while referring to plane 1. This means that plane 1 has 0mm as it was set as the reference plane. In the figure, all the planes are being denoted as P.

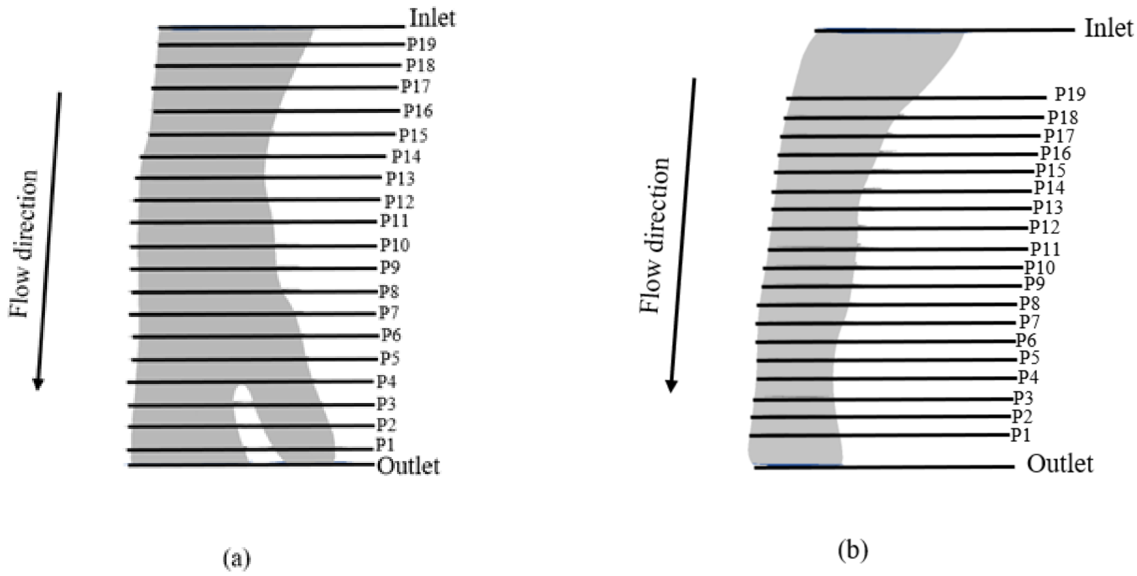


Fig. 1. Horizontal planes in the airway, (a) pre-treatment condition (b) post-treatment condition

Figure 2 depicts the airway's cross-sectional area in nineteen various planes for both types of conditions. The planes being portrayed are in the z-direction (flow direction). The figure shows that the respondent's airway around the retroglossal area had significantly decreased after the mandibular setback surgery. For the pre-treatment condition of the airway, the minimum cross-sectional area is 3.477 cm^2 which was located at 30 mm from the reference plane. However, for the post-treatment condition of the airway, the minimum cross-sectional area of the airway is located at 7.5 mm from the reference plane with an area of 2.182 cm^2. Area of the airway plays a significant role as the minimum area of the airway might determine the pathogenesis of the airway obstruction. Thus, the focus of the analysis is being directed towards the plane with the minimum cross-sectional area of the post-operation airway, which is P4 for both types of conditions.

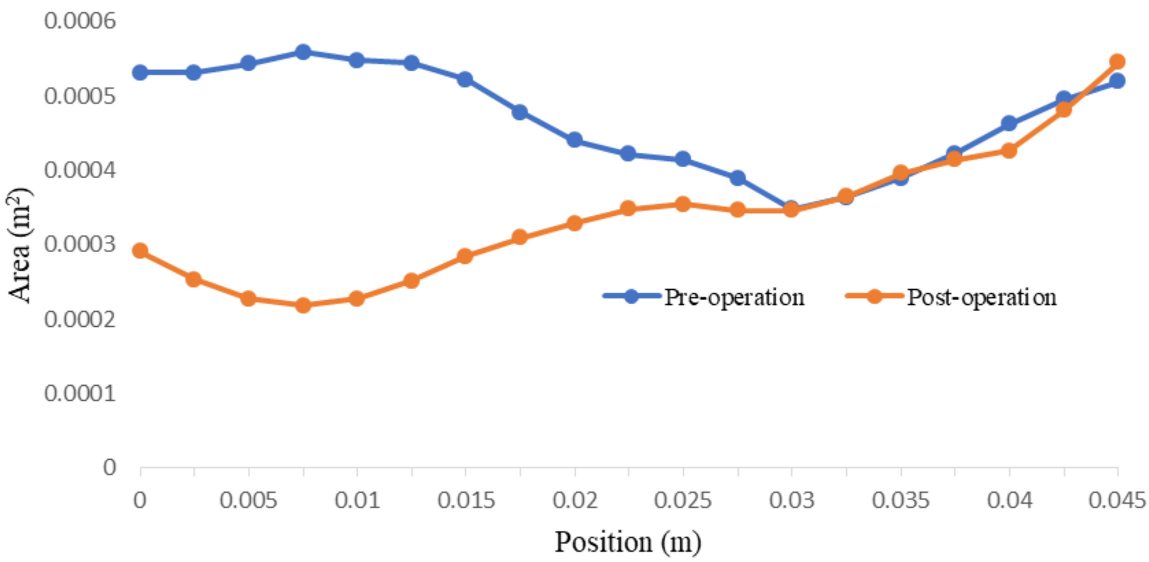
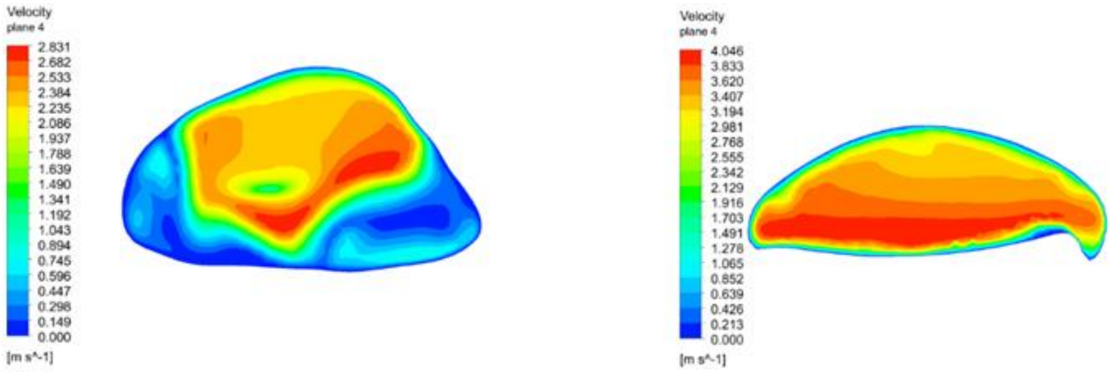


Fig. 2. The cross-sectional area along the flow direction of the airway in both conditions

3.2 Flow Pattern

As seen from Figure 3, the critical plane for post-treatment, which is plane 4, the highest velocity is observed to be 4.046 m/s while in pre-treatment condition is 2.831 m/s. It can be observed that the post-operation airway possesses a higher velocity magnitude compared to in pre-operation airway. This difference in velocity value happened due to the airway's significantly lower minimum cross-sectional area in the post-treatment condition. This lower cross-section of area induced a higher pharyngeal jet than the pre-treatment condition. Thus, a higher velocity value can be observed in the post-treatment condition. According to a study, a turbulent jet flow will be induced when an area in the upper airway is restricted. This flow is commonly referred to as "pharyngeal jet flow." The decrease in the cross-sectional area of the pharyngeal airway will influence the airway flow as the airflow might induce high aerodynamic forces when passing through it. This will also affect the smoothness of the airflow due to the area restriction. A high aerodynamic forces induction might cause laxity in the upper airway tissue and cause collapsibility of the upper airway.



(a) (b)

Fig. 3. Velocity contour in horizontal plane 4 for both types of conditions, (a) pre-operation (b) post-operation

Figure 4 illustrates the velocity magnitude along the upper airway for both conditions. The figure shows that the post-treatment condition possesses a higher maximum velocity value than the pre-treatment condition. It can be seen that in both conditions, the maximum velocity magnitude occurs around the most minimum area of the airway. However, the flow pattern in the pre-treatment condition seems to be increasing steadily compared to the flow in the post-treatment condition, which has the velocity distribution of uneven velocity profile. The velocity is being transported downstream of the airway. After the restriction of the area occurs, the velocity distribution is being significantly affected by the pharyngeal jet flow. This jet will carry the air along the airway into the laryngeal pharynx. Thus, this is why the velocity distribution becomes uneven at the laryngeal pharynx.

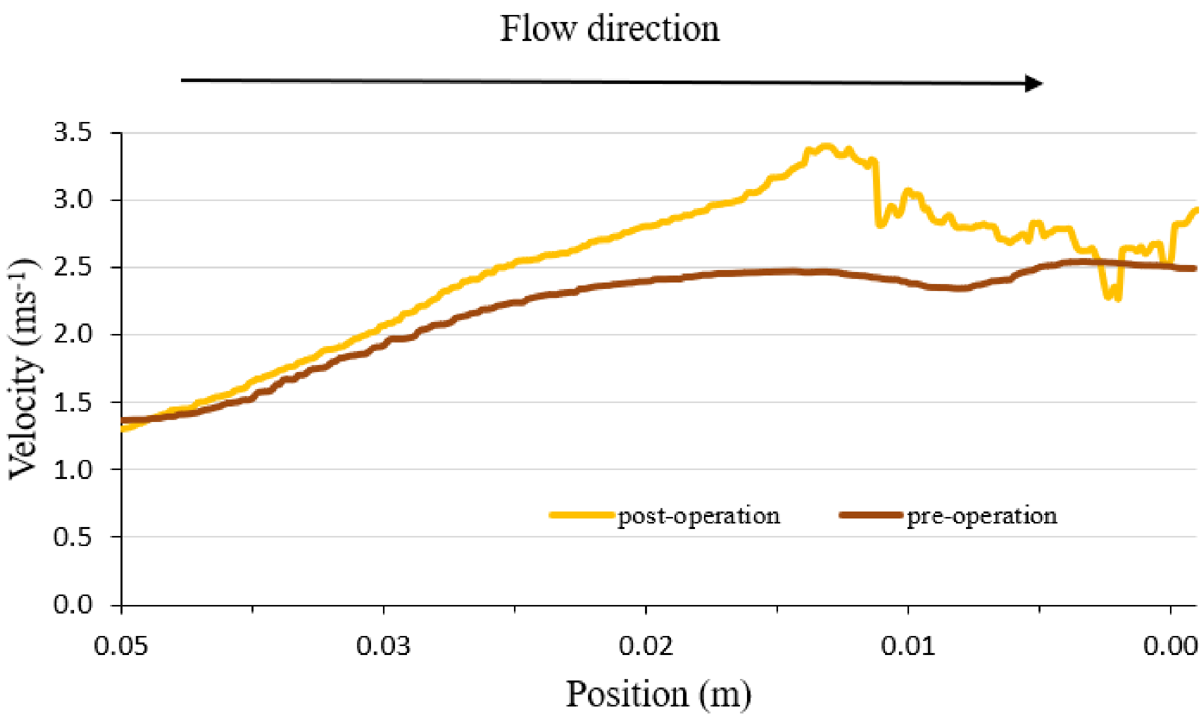


Fig. 4. Velocity magnitude along the airway in both types of conditions

3.3 Pressure

Figure 5 portrays the velocity contour at plane 4 in both airway conditions. The maximum pressure drops are -0.553 Pa and -1.427 Pa for pre-treatment and post-treatment conditions, respectively. This shows that the pressure drops at plane 5 are more significant post-treatment than pre-treatment. When a jet flow is induced, it carries a high velocity, which simultaneously induces a high-pressure drop. This condition will provide a high aerodynamic force towards the pharyngeal airway [15]. This aerodynamic force will produce a high wall shear stress. A high-pressure drop will then cause a high inward pressure force. This high wall shear stress might become the primary obstruction in the airway [16]. This explains why the maximum pressure drop value in the post-treatment condition at P4 is higher than in the pre-treatment condition. Plane 4 in the post-treatment condition is considered the narrow region that induced a jet flow.

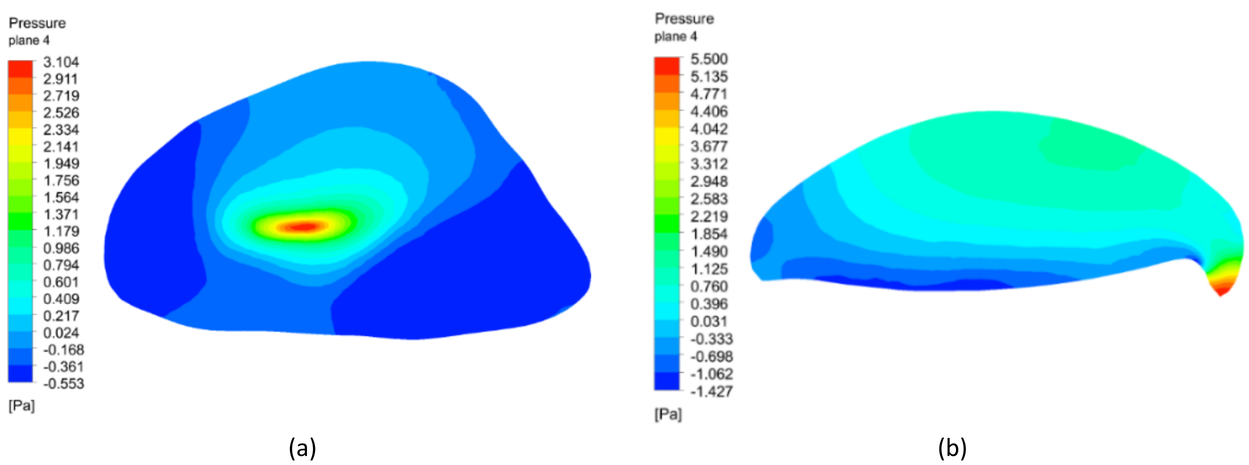


Fig. 5. Pressure contours in horizontal plane 4 for both types of conditions, (a) pre-operation (b) post-operation

Figure 6 depicts the pressure distribution along the pharyngeal airway in both types of conditions. From the figure, it can be observed that the pressure drop in the post-treatment condition is more significant compared to in the pre-treatment condition. The maximum pressure drop along the airway is located almost in the same regions for both conditions. Due to its critical cross-sectional area, the post-treatment possessed a more significant pressure drop than the pre-treatment condition. The post-treatment condition's critical cross-sectional area is smaller than the pre-treatment condition. Thus, the jet flow being induced is also larger and resulting in a more significant pressure drop.

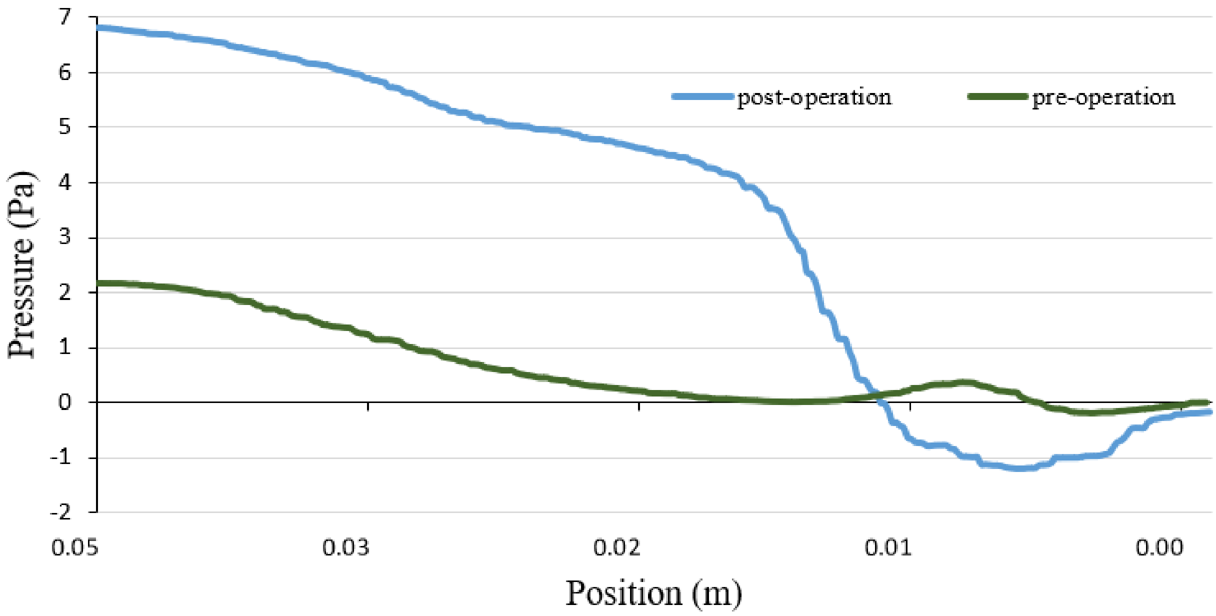


Fig. 6. Static pressure along the airway in both types of conditions

3.4 Wall Shear Stress (WSS)

In this respondent's case, the highest wall shear stress value can be observed at the laryngeal pharynx region in the pre-treatment condition. It possesses a value of 3.935 × 108 Pa. The contour of the wall shear stress along the pre-treatment condition wall can be observed as being presented by Figure 7(a). Due to the region that affected small, a more precise image is being projected by Figure 7(b) to enhance the contour of the wall shear stress. In the meantime, the highest wall shear stress value in the post-treatment condition is being depicted in Figure 7(c). With a value of 1.842 × 109 Pa, it can be said that the value of wall shear stress in the post-treatment condition is more significant compared to in pre-treatment. More precise visualization of the contour distribution at the affected region in post-treatment is being presented in Figure 7(d). The affected region in the post-treatment condition is also observed at the larynx region.

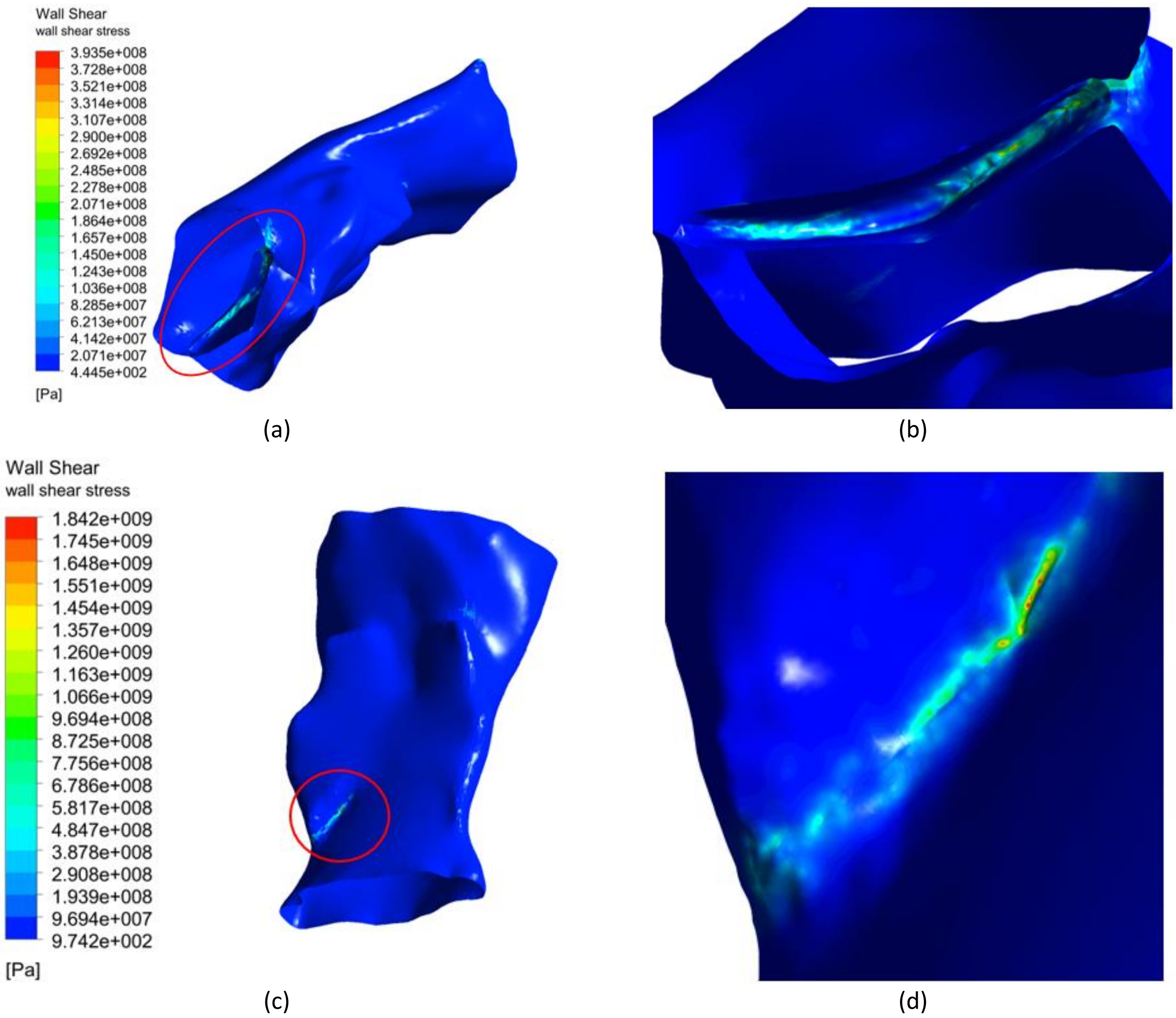
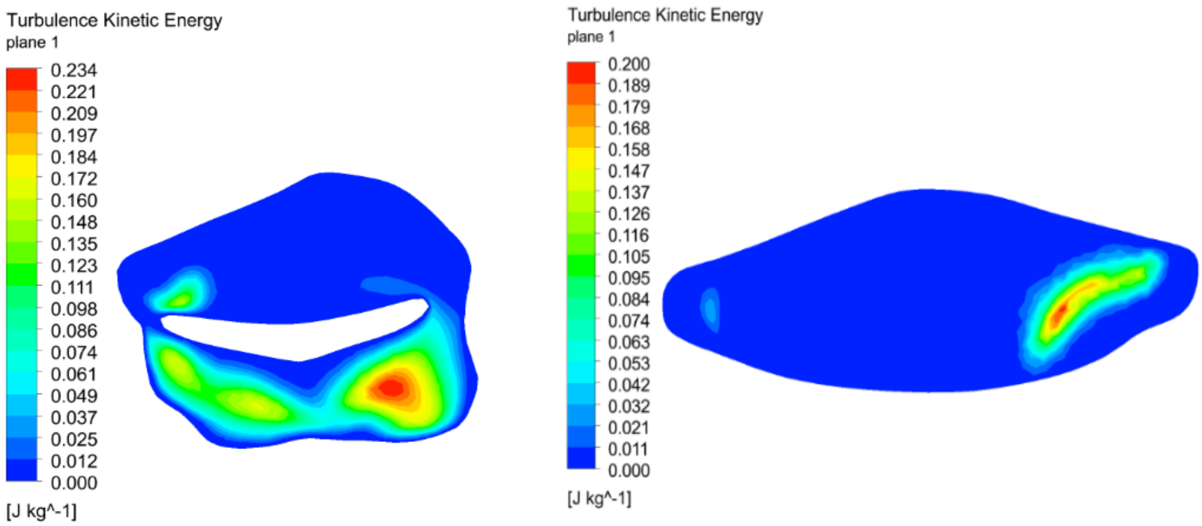


Fig. 7. Wall shear stress contour along the pharyngeal airway wall, (a) pre-treatment condition (b) magnified image of the affected region in pre-treatment (c) post-treatment condition (d) magnified image of the affected region in post-treatment

When a high wall shear stress occurs in an airway, it indicates a fluctuating environment within the region. This means that the magnitude and the direction of the forces induced acting on the airway wall at that region change rapidly. The inward pressure force induces this WSS from the high aerodynamic force. A relatively high WSS might become the factor of pharyngeal airway occlusion as the tissue in the airway may collapse. The post-treatment condition possessed a higher WSS value than the pre-treatment condition based on the data presented. However, by referring to the figure provided, it can be seen that the affected area in both types of conditions is relatively small. This is due to the weak pharyngeal jet induction in the airway. Thus, in this respondent's case, the airway obstruction might not be occurring in any condition. However, the value of WSS induced in both types of conditions is relatively high. Even though the distribution of WSS along the airway is not widely distributed and only focused in a small region, due to the high WSS at the region, the affected region might come across with the damage of the airway tissue.

3.5 Turbulent Kinetic Energy (TKE)

In the pre-treatment condition, the highest TKE can be observed at plane 4 with a value of 0.273 Jkg^{-1}. In the post-treatment condition, the highest TKE value at this plane is observed to be 0.028 Jkg^{-1}. These values can be observed in Figure 8. From here, it can be said that the TKE value in the pre-treatment condition is higher compared to in the post-treatment condition.



(a) (b)

Fig. 8. Turbulent kinetic energy contours in horizontal plane 4 for both types of conditions, (a) pre-operation (b) post-operation

From Figure 9, which shows the TKE along the airway in both conditions, it can be seen that the TKE value in the post-treatment condition is significantly higher compared to in the pre-treatment condition. The lowest value of TKE occurring in the post-treatment condition is located in the same region with the highest value of TKE in the pre-treatment condition. They are both located near the retroglossal area. If a strong jet flow is induced, a strong recirculation flow might also occur. This recirculation flow will dissipate the jet flow kinetic energy by decreasing the flow velocity. Thus, high turbulence will be induced. If no area restriction occurs, the jet flow will preserve its energy as it passes through the airway. This condition explains how the TKE value in the pre-treatment condition is more significant than in the post-treatment condition [17]. This is due to the recirculation that occurs in pre-treatment due to the separation of flow at the laryngeal pharynx region. However, there seems to be no recirculation of flow in post-treatment conditions.

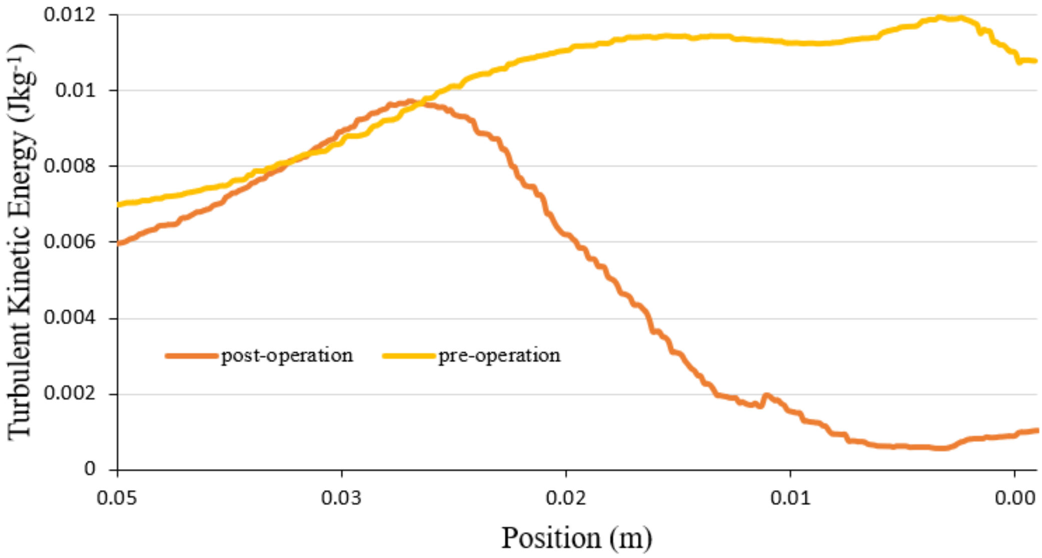


Fig. 9. Turbulent kinetic energy along the airway in both types of conditions

4. Conclusion

3D simulations are performed to study the pharyngeal airway effect of mandibular setback surgery. The flow characteristic for patient mandibular prognathism surgery before and after mandibular setback was compared. The simulations are performed with the aid of CFD tools to model the pharyngeal airway, and the strength of this tool in modeling and solving the Navier-Stoke equations is being presented in this study. This study found that the respondent did not possess Obstructive Sleep Apnea (OSA) after the mandibular setback surgery. After the surgery, the pharyngeal airway decreases significantly. The pressure drop, flow pattern, airway wall shear stress (WSS), and turbulent kinetic energy (TKE) seem more significant after the critical plane in the post-treatment condition [18]. However, these factors did not contribute to the OSA as it is not large enough to become the cause of OSA. The surgery can be assumed as a success since it did not become the etiology of OSA towards the respondent.

Nonetheless, the value of the WSS after the surgery is relatively high, with a value of 1.842 × 109 Pa. This high value of WSS can induce injuries to the airway wall. In the meantime, due to only a tiny affected region regarding this factor, it did not become an obstruction towards the airway. Even though this factor did not obstruct the airway wall, it gradually may potentially cause high cycle fatigue of the lumen wall. This presented work is expected to project a more precise visualization of the airflow characteristics and enhance the understanding of the medical practitioners in the OSA research field.

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