NASAL AIRFLOW SIMULATION OF PATIENT WITH SEPTAL DEVIATION AND ALLERGY RHINITIS

by

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Thesis submitted in fulfillment of the requirements
for the Bachelor Degree of Aerospace Engineering (Honors)

June 2017

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ABSTRACT

This is a research based on numerical simulation a patient's nasal airflow by using computational fluid dynamic (CFD). The CT scans of patient with both septal deviation and allergy rhinitis is obtained from Advanced Medical and Dental Institute (AMDI) to study the impact of both diseases to human nasal cavity. The three-dimensional (3D) nasal cavity model of the patient is being constructed by using InVeselius 3.0. The 3D nasal model is then being imported to CATIA V5 for modification and finally imported into ANSYS FLUENT for the numerical solution. The results and effects of these two diseases on a patient are being analyzed on geometrical, cross-sectional area, mass flow rate, pressure and velocity magnitude. The cross-sectional area, velocity magnitude and velocity contours for the four main surfaces: vestibule, nasal valve, middle turbinate and nasopharynx are being analyzed and compared with the standardized nasal cavity as well.

SIMULASI ALIRAN UDARA RONGGA HIDUNG PESAKIT DENGAN SISIHAN SEPTAL DAN ALAHAN RINITIS

ABSTRAK

Penyelidikan ini adalah berdasarkan simulasi aliran udara rongga hidung pesakit dengan menggunakan dinamik bendalir pengiraan (CFD). Imbasan CT pesakit dengan kedua-dua sisihan septal dan alahan rinitis diperolehi dari Institut Perubatan dan Pergigian Termaju (IPPT) untuk mengkajikan kesan kedua-dua sakitan ini terhadap rongga hidung manusia. Model tiga dimensi (3D) rongga hidung pesakit telah dibina dengan menggunakan InVeselius 3.0. Model rongga hidung tersebut akan kemudiannya diimport kedalam CATIA V5 untuk pengubahsuaian dan akhirnya diimport kedalam ANSYS FLUENT untuk penyelesaian berangka. Keputusan dan kesan kedua-dua penyakit pada pesakit yang akan dianalisis pada geometri, luas keratan rentas, kadar aliran jisim, tekanan dan halaju magnitud. Kawasan keratan rentas, magnitud halaju dan halaju kontur untuk empat permukaan utama: vestibule, injap hidung, turbinate tengah dan nasofarinks akan dianalisis dan dibandingkan dengan rongga hidung seragam yang siap dibina.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude to my supervisors, Dr. Lee Chih Fang and Dr. Parvathy Rajendran. I need to thank Dr. Lee who has helped a lot at the beginning of this research, she guided me step-by-step in completing this research, this project cannot be finished smoothly without her guidance. Besides, I would express my appreciation to Dr. Parvathy who has provided guidance for winding up the whole project, without her help, this thesis would not have been done. In completing this project, my friend, Ms. Foo Kar Yen has helped me a lot by giving comments and support all the time, I need to thank her for helping me tirelessly. Moreover, I would like to thank every staff in School of Aerospace Engineering that helped me throughout this project, especially for the assistant engineer in CATIA Lab, Mdm. Rahayu bt. Dorahim @ Abdul Rahim, thanks for willing to lend your hand when I needed. Lastly, thousands of thanks to all my coursemates for their understanding, encouragements and supports.

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Date:

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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CHAPTER 1

INTRODUCTION

1.1 General Overview

The respiratory system is a complex biological system comprises of several organs that facilitates the inhalation and exhalation of oxygen and carbon dioxide in living organisms, in other words, breathing. In fact, the respiratory system is composed of the biological structures: nose and nasal cavity, mouth, pharynx, larynx, trachea, bronchi and bronchioles, lungs and the muscles of respiration [1],[2]. The nose is the primary opening for the respiratory system that made of bone, muscle and cartilage, while the nasal cavity constitutes the main external opening of the respiratory system. Nasal cavity is used for air inhalation and warms and moistures the air as it entered, acting as filtration and purifying the air by preventing the dust, mold, pollen and other contaminants reaching the internal components of body. During exhalation, the warm air that is eliminated returns the heat and moisture back to the nasal cavity, so this forms a continuous process [3]. Therefore, nasal cavity is one of the most important parts in human respiratory system. Nasal obstructions including deviated nasal septum, enlarged turbinates, nasal polyps, enlarged adenoids, tumors and nasal congestion can cause difficulties in breathing. There are two main nasal obstructions being discussed, which are septal deviation and allergy rhinitis.

1.2 Septal Deviation

The nasal septum is the bone that divides one side of the nose from the other. It is rarely perfectly straight, it is composed of a central supporting skeleton covered on each side by mucous membrane [4]. The front portion of this natural partition is a firm but bendable structure made mostly of cartilage and is covered by skin that has a substantial supply of blood vessels, it is slightly crooked in over 80% of people [5]. When the septum is so crooked or deviated that it blocks the nasal passage, then a surgical operation called a submucosa resection will restore clear breathing. Septal deviations play a critical role in nasal obstruction symptoms, aesthetic appearance of the nose, increased nasal resistance, and sometimes snoring [6],[7]. Symptoms of a deviated septum include infections of the sinus and sleep apnea, snoring, repetitive sneezing, facial pain, nosebleeds, difficulty with breathing and mild to severe loss of the ability to smell [4],[8].

1.3 Allergy Rhinitis

Rhinitis is defined as inflammation of the nasal mucosa and affects up to 40% of the population [9]. Among all causes of mucosal inflammation, allergic rhinitis is the most common, affecting 1 in 6 individuals [10]. Allergy rhinitis is an allergic response to specific allergens. There are two types of allergic rhinitis: seasonal and perennial. Seasonal allergic rhinitis can occur in spring, summer and early fall. It is usually caused by allergic sensitivity to airborne mold spores or to pollens from grass, trees and weeds. Perennial allergic rhinitis experience symptoms year-round. It is usually caused sensitivity to dust mites, cockroaches, or animal dander. Some people may experience both types of rhinitis, with perennial symptoms getting worse during specific pollen seasons [11],[12]. Allergy rhinitis is one of the most common diseases affecting adults. It is the most common chronic disease in children in the United States today and the fifth most common chronic disease in the United States overall. Allergy rhinitis is estimated to affect nearly 1 in every 6 Americans and generates $2 to $5 billion in direct health expenditures annually [10].

1.4 Computational Fluid Dynamics

To better understand the physiology of the nasal cavity, this study makes use of Computational Fluid Dynamics (CFD) methods to present flow patterns and compared the results. CFD has become a fast and convenient research tool to study airflow in the human airway especially when investigating heat and humidity transfer, which is not easy to study by using other experimental techniques [13],[14],[15],[7]. CFD is useful to picture the airflow mechanics in complex geometry such as human nasal cavity, the simulation results with cross-sectional area, pressure and velocity are being discussed and analyzed.

1.5 Model Resource

In this project, the CT scans of a female adult patient with both septal deviation and allergy rhinitis is obtained from Advanced Medical and Dental Institute Universiti Sains Malaysia (AMDI, USM) on 14 April 2016 as shown in Figure 1 below. The 3D nasal cavity model will be developed from CT scans and export to CATIA V5 then the airflow simulation will be run using CFD techniques. The result will be compared with a standardized nasal cavity to analyze the impact of septal deviation and allergy rhinitis on nasal cavity.

Figure 1 CT Scan of Patient Obtained from AMDI

1.6 Problem Statement

Nasal Obstruction has cause inconveniences for human daily life as the airway behaviour is different from healthy person. Septal deviation that causing the septum to buckle or deviate has been found in around 1 to 20% in children, with rates around 13% in teenagers [6],[16]. Analysis of adult skulls from multiple ethnic backgrounds has found even higher rates, with approximately

80% [16]. While allergy rhinitis affects almost one quarter of the population worldwide and it significantly impairs quality of life [17],[9]. Patients suffered from allergy rhinitis decrease daytime productivity at work or school and reduce sleep quality [17]. Both diseases are causing severe negative influences in human daily life, therefore, by studying the airflow in patient's nasal cavity model, the impact of these diseases to human airway can be analyzed by comparing the patient's nasal cavity model to a standardized nasal cavity model by Lee et al. [18]. Solving these two of nasal obstruction problems are helping about a quarter of worldwide to live without being troubled by both diseases.

1.7 Research Objectives

The research work described in this thesis is performed based on the following objectives:

i. To develop a 3D nasal cavity model of a septal deviation and allergy rhinitis patient.

ii. To study airflow behaviour of human nasal cavity of a septal deviation and allergy rhinitis patient.

iii. To carry out numerical simulations of the nasal cavity of a septal deviation and allergy rhinitis patient.

iv. To compare and analyze the impacts of septal deviation and allergy rhinitis patient's nasal airflow with a standardized human nasal cavity.

1.8 Research Scope

This research is done on a Malaysian female adult patient with septal deviation and allergy rhinitis. A 3D nasal cavity model of patient's airway is being constructed and then compared with a standardized Malaysian female adult nasal cavity. The nasal cavity model is constructed from CT scans obtained from AMDI, USM by using an open-sourced software called InVesalius 3.0. The 3D model is then being imported into CATIA V5 for smoothing the surface, all topological edges should be removed in this part. Finally, the model is being imported into ANSYS FLUENT for simulation running of only inhalation process. As this patient is only suffered from septal deviation and allergy rhinitis, the research is only focus on these two diseases. The models are being compared with the geometrical structure, cross-sectional area, pressure and velocity to see the differences from above aspects between both models.

1.9 Thesis Outline

This thesis contains five main parts, which are introduction, literature review, methodology, result and discussion, and conclusion. Introduction describes the general overview of this research, including denotation and explanation of diseases, which are septal deviation and allergy rhinitis. Besides, definition and function of CFD is also being discussed in this part. The introduction part ends with the problem statement, objectives and scope of this research. Literature review discussed about the previous researchers' studies that is related to this research. Methodology comprises the fundamental theories involved and steps to complete this research, including the steps of model reconstruction to simulation running. In result and discussion part, the numerical results obtained from simulation running of the patient's nasal cavity are being analyzed and discussed in figures, tables and graphs for easy to comprehend, then comparison with the standardized model is also being discussed in this part. Lastly, the conclusion significant the end of this thesis, the results as well as the future recommendations for similar research are being concluded.

CHAPTER 2

LITERATURE REVIEW

There are several researchers have carried out similar research on human nasal cavity, some are focused on human nasal anatomy; some focused on human nasal cavity airflow; some focused on disease case while some focused on the CFD studies. Those researchers have made a lot of contribution in improving human daily lifestyle by studying the airflow simulation of human nasal cavity.

2.1 Human Nasal Anatomy

Some researchers have done the study about human respiratory system. Vit et al. and Tu et al. have focused on computational method of human respiratory system [19],[1]. Vit et al. have reported about the respiratory airways that cause resistance to air flow during inhalation and exhalation. In the paper, the knowledge of pressure gradient that is necessary to transport the air from the nose to pulmonary alveoli is used as boundary conditions for CFD simulations of aerosol transport. Besides, this article deals with the description of the mathematical equations defining the pressure gradient and resistance in the bronchial three and describes the geometry used in the calculation. On the other hand, Tu et al. have reviewed the descriptions, locations, geometry, and naming conventions for the anatomical parts as well as the fundamentals of the anatomy and physiology of the respiratory system to view the basis for decision-making when reconstructing the model. As nasal cavity is one of the important part in human respiratory system, Tu et al. have studied the function of nasal cavity from the nostril to the pharynx on the air behaviour of inhalation and exhalation, and the function of paranasal sinuses as well.

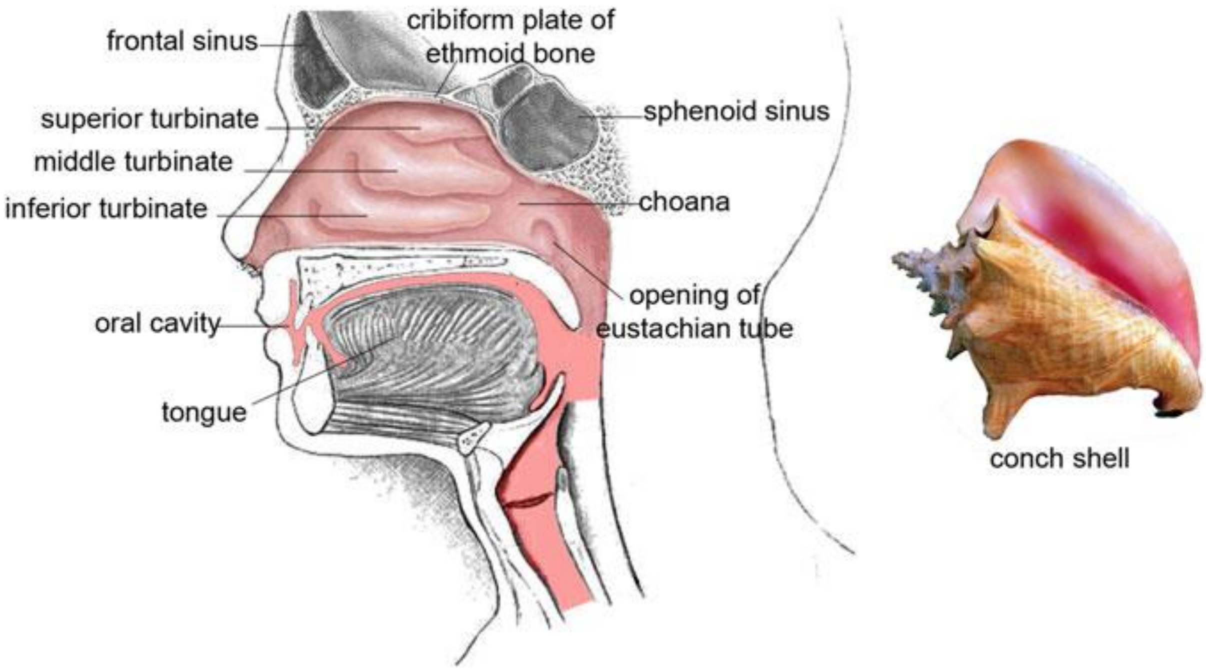


Figure 2 Structure of The Internal Nasal Cavity. The turbinates are also referred to as concha because of it resemblance to a conch shell [1]

2.2 Human Nasal Cavity Airflow

Many researchers have discussed about the airflow of healthy human nasal cavity. Elad et al. have studied on the knowledge of human nasal cavity airflow and made comparison between airflow of nose breathing and mouth breathing [2],[20]. He focused his studies in mechanics of human airflow passage and the impact of the complex structure of nasal cavity to human breathing behaviour. The nasal air conditioning characteristics are explained detailly in his paper. In Kelly et al. paper, the detailed airflow pattern of human nasal cavity is being discussed [21]. In this paper, particle image velocimetry is used to determine two-dimensional instantaneous velocity vector fields in parallel planes to have a clear figure on how air flows in human nasal cavity with the mass flow rate of 125 mL/s. The negative nasal cavity airway model is fabricated from 26 computed tomography scans by using rapid prototyping techniques. To see the airflow pattern clearly, Kelly et al. have created coronal planes throughout the nasal cavity as shown in Figure 3 below.

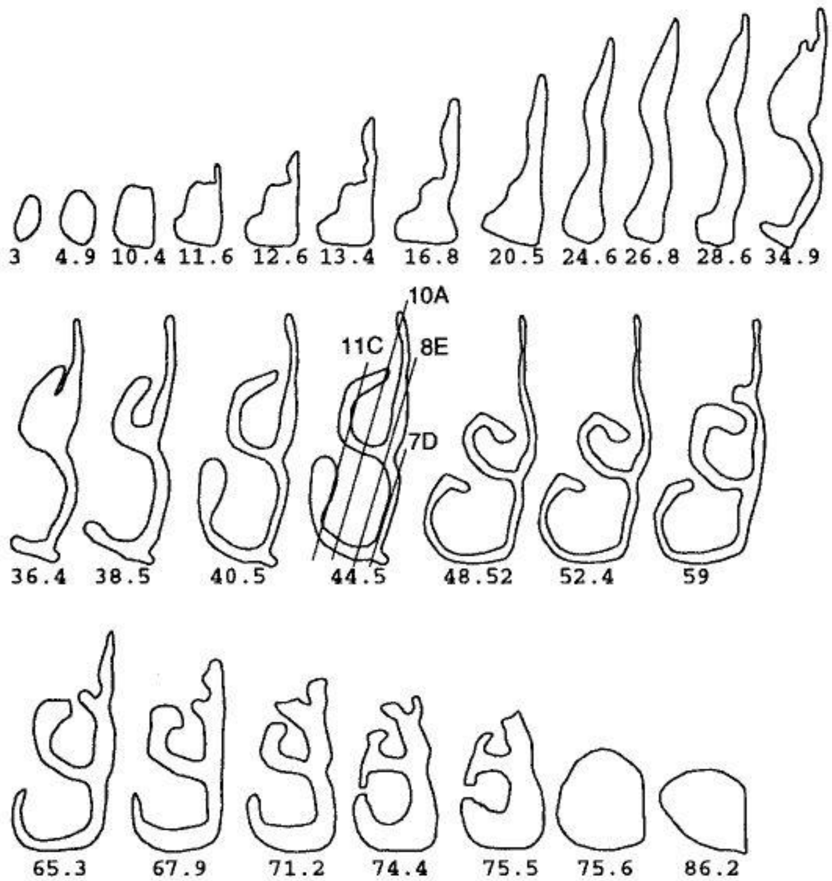


Figure 3 Coronal Computed Tomography Scan Data of a 25-yr-old Male [21]

Same goes to Wang et al. that have constructed numerical models of six 3D human right nasal cavities from computed tomography data and run the airflow simulations with CFD software for quiet breath on six models. The simulation results are validated by comparing with the particle simulations results [22]. Even Kelly et al. and Wang et al. are only focused on right nasal cavity model, the methods and theories behind are needed to complete this research.

2.3 Disease Case

Although most of the researches are done with healthy human nasal cavity, there are still having variety of researchers interested in disease case. Kim et al. have discussed about the imbalanced nasal cavity that caused by septal deviation [4]. Total six nasal cavities models with septal deviation are constructed and discussed on the impact of this disease to the airflow to nasal physiology and pathology. Figure 4 below shows the velocity streamline and velocity contour of model that Kim et al. have studied.

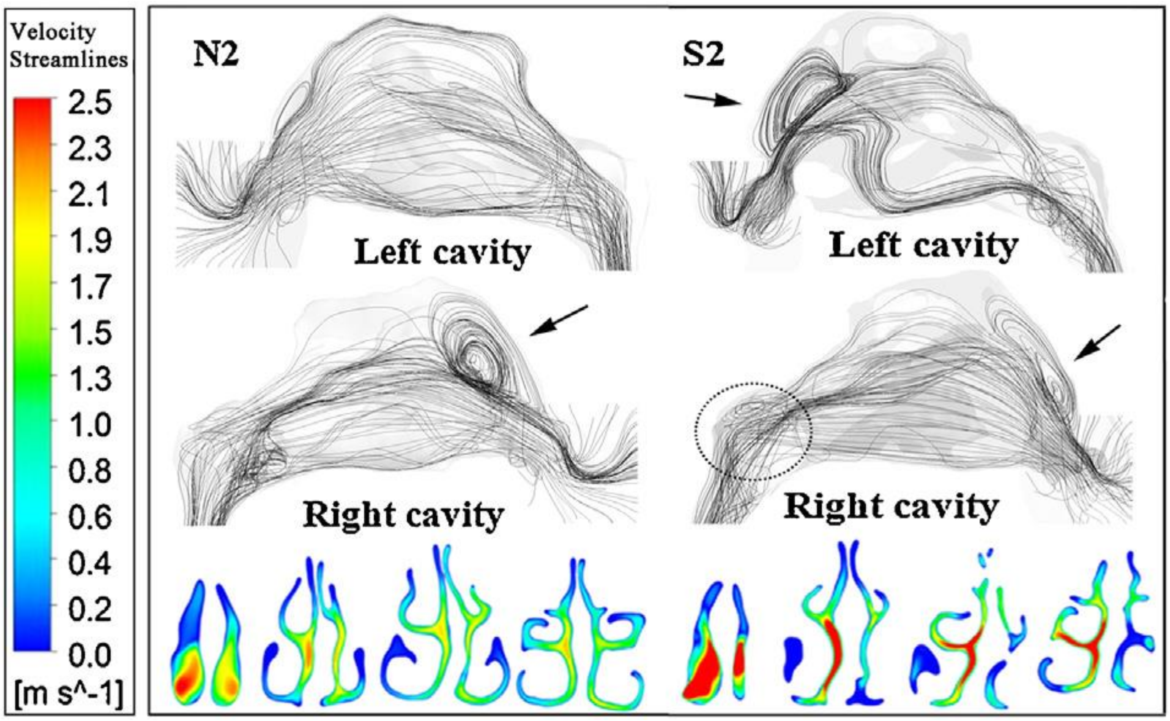


Figure 4 Streamline and Coronal Velocity Magnitude Distribution [4]

There are few researchers focused their studies on the impact of nasal obstruction diseases to human nasal cavity. Garcia et al., Wakayama et al. and Stewart et al. are also have done their research on nasal disease cases [23],[24],[17]. These researchers focused their studies on using CFD technique to investigate the impact of nasal obstruction diseases to human daily life, their studies have mainly done on the geometrical construction of disease nasal cavities and the analysis of numerical solution from simulation running. The 3D nasal cavity model with nasal obstruction constructed by Wakayama et al. is shown in Figure 5 below.

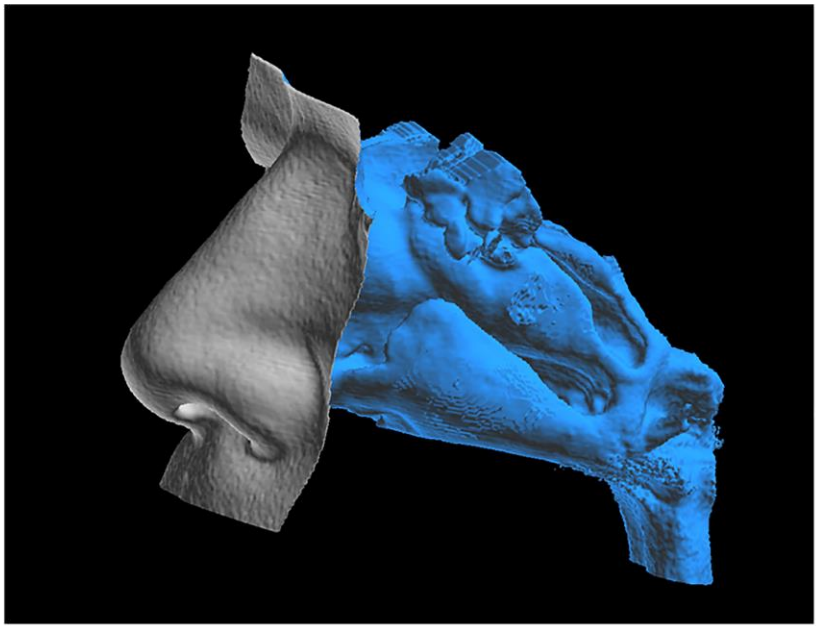


Figure 5 .STL Model of Nasal Cavity [24]

2.4 Computational Fluid Dynamics

CFD seems to be one of the most useful technique to determine the flow in a complex geometry structure. To determine the airflow in a human nasal cavity, CFD technique is used to simulate the flow pressure, velocity as well as the wall shear stress. Lin et al. have described a computational framework for multiscale simulation of gas flow in subject-specific airway models of the human lung [25]. The framework consists of five major components: accurate extraction of airway geometry from MDCT image data sets, geometrical modeling of airway trees, novel 3D and 1D coupled mesh generation, 3D high-fidelity CFD techniques for turbulent and transitional flow, and CT-derived subject-specific physiological boundary conditions. This work demonstrates the importance of multi-scale simulation of pulmonary gas flow for accurate prediction of flow characteristics at large and small airways and their interactions. Similar method for Smith et al., Bruening et al., Kim et al. and Inthavong et al. that have studied on how useful for using CFD technique to picture the airflow behaviour and mechanics in human nasal cavity [26],[27],[13],[14].

Laminar flow is used to see the air conditioning of human nasal cavity in CFD software setting, it was found that the decreasing of cross-sectional area of passageway gives significant differences in numerical results. Planes within the nasal cavity can be created using CFD software, planes are created to picture the 2D figure of flow mechanics and flow distribution.

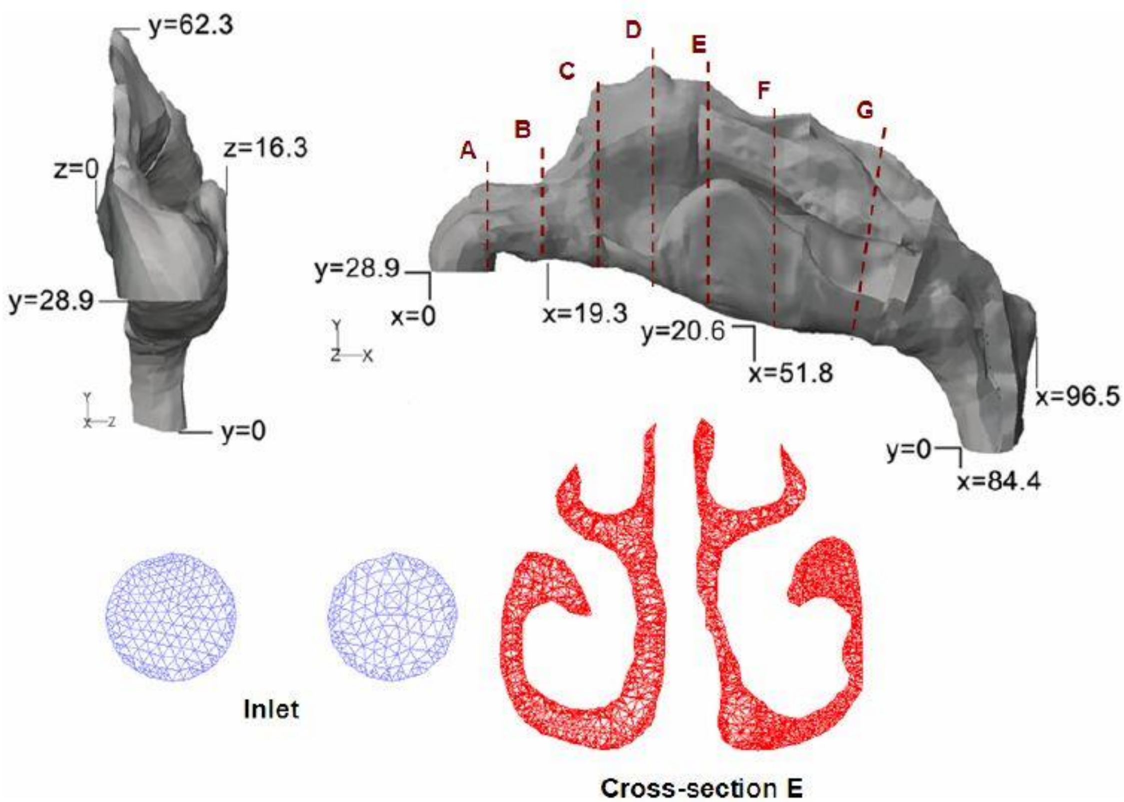


Figure 6 Nasal Cavity Geometry Measurement and Cross-sectional Mesh [14]

CHAPTER 3

METHODOLOGY

The CFD technique has the capability to predict the airflow and particle deposition in the airway geometries of nasal cavity [25]. Thus, CFD is being highly used in airflow prediction of complex structure. In this case, ANSYS FLUENT will be used for the simulation to obtain the accurate airflow simulation of patient's nasal.

The DICOM files of a female adult patient that developed from the CT scans are obtained from AMDI. Then the DICOM files are being imported into InVesalius 3.0 for constructing the 3D nasal model of the patient, then being imported as cloud point in CATIA V5. The modification will be performed in CATIA V5 before exporting to ANSYS FLUENT for meshing. Next, the airflow simulation of different mass flow rate will be run to get detailed overview on the patient with septal deviation and allergy rhinitis. The CFD results of fluid mechanical properties are finally being analyzed and compared with healthy standardized female adult nasal cavity model to figure out the impact of septal deviation and allergy rhinitis.

3.1 Model Reconstruction

InVesalius 3.0 is an open-sourced software for virtual modeling, it has the capability to obtain an accurate model of the anatomical region to be studied, good quality medical images are necessary [28]. The DICOM files from CT scans of a female patient are being imported into InVesalius 3.0. The number of 2D slices in 3 axes is shown in Table 1 below, as the study is only focus on the nasal cavity, the number of slices that not involved the nasal cavity is not considered. An inverted model of patient's airway is being constructed by filling the space that the air will flow by, which including the 2D slices mentioned in Table 1. In this software, the airway of subject can be shown as Figure 7 below to make sure the airway model is being constructed on the correct place as only nasal cavity being considered in this study.

AXIS	TOTAL NUMBER OF SLICES	NUMBER OF SLICES USED
AXIAL	238	103 – 171
CORONAL	511	216 – 427
SAGITTAL	511	215 – 301

Table 1 Number of 2D Slices CT Scans of Patients

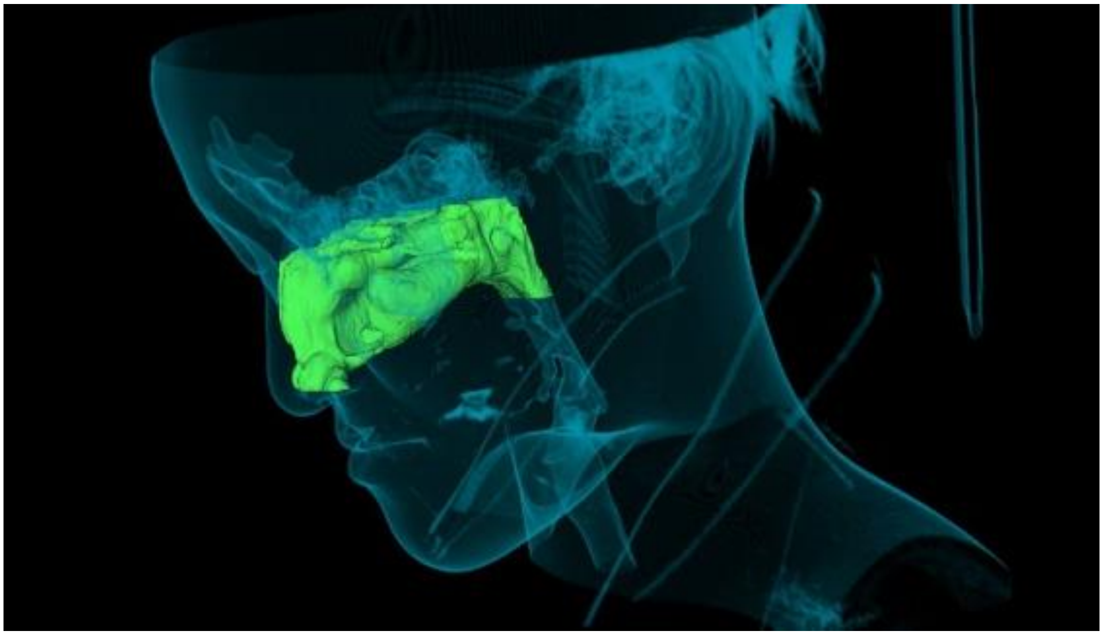


Figure 7 3D Model Construction with Patient's Airway

Then the model will be exported as .STL file and imported into CATIA V5 as the cloud point. The model is being smoothen and modified after the mesh creation in CATIA V5. The surface and volume creation will also be done in CATIA V5 for constructing a solid model. Then the 3D model is finally saved as .STEP file to import into ANSYS FLUENT for simulation running. The steps of 3D model reconstruction are shown in Figure 8 below.

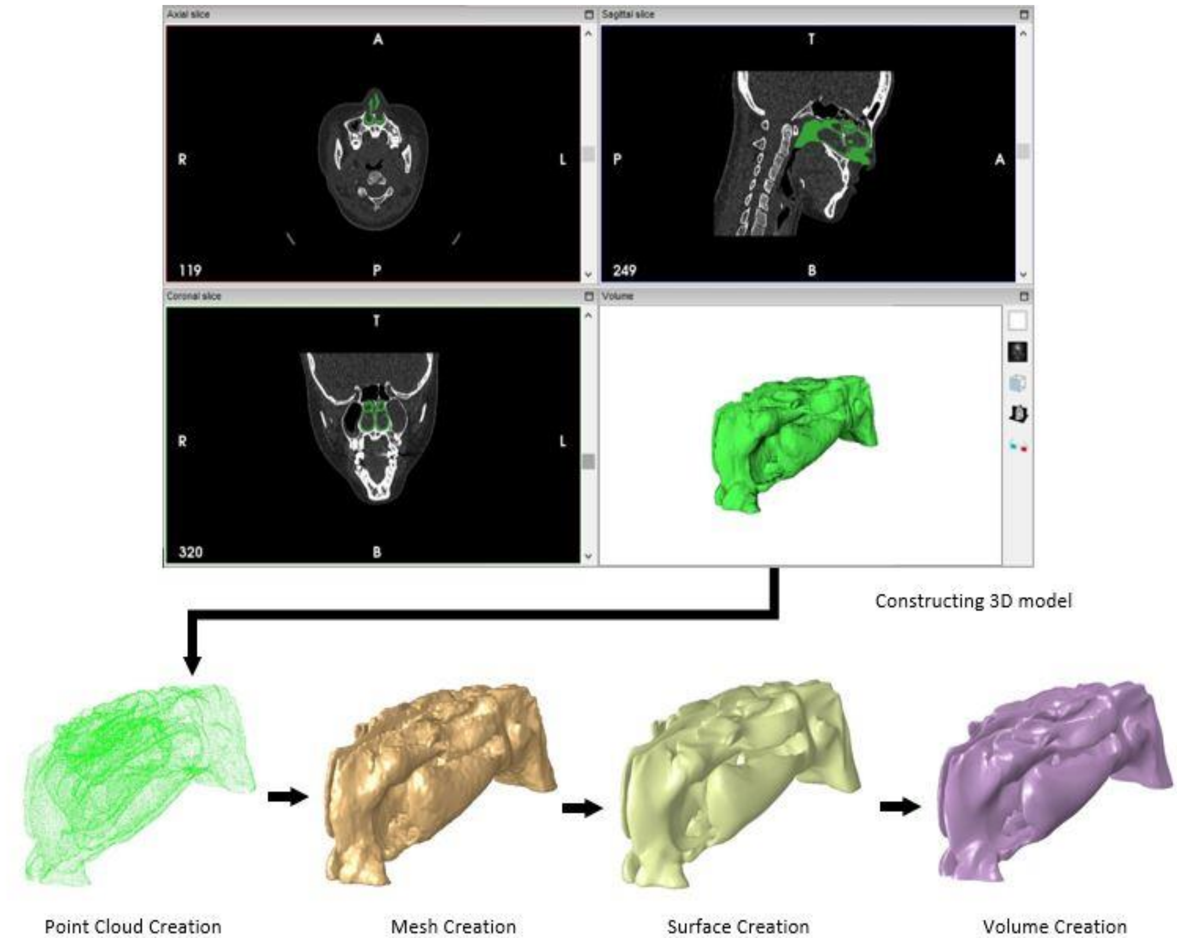


Figure 8 Steps from CT Scans to Solid Model

3.2 Simulation Running

The first step to be done before simulation being run is to mesh the model. The .STEP file model is being imported into ANSYS FLUENT for meshing. The model import into ANSYS FLUENT is shown in Figure 9 below. The nasal wall was assumed to be rigid, with no slip boundary condition, and effects of mucous were assumed to be negligible [29],[30]. The nostril inlet was defined by mass flow inlet, and the outlet at nasopharynx was defined by the outflow boundary condition. Any backflow at the outlet was assumed to be at 32.6˚C and 100% relative humidity as imported into ANSYS FLUENT [15],[21]. The pressure based model is used for this simulation, as the density of air is assumed constant throughout the geometry [26],[19]. The flow of mucus was not considered due to its minimal thickness and low velocity [29]. The model is being meshed for 3 types of meshing for the mesh dependency study as shown in Figure 10 below. The meshing element is shown in Table 2 below.

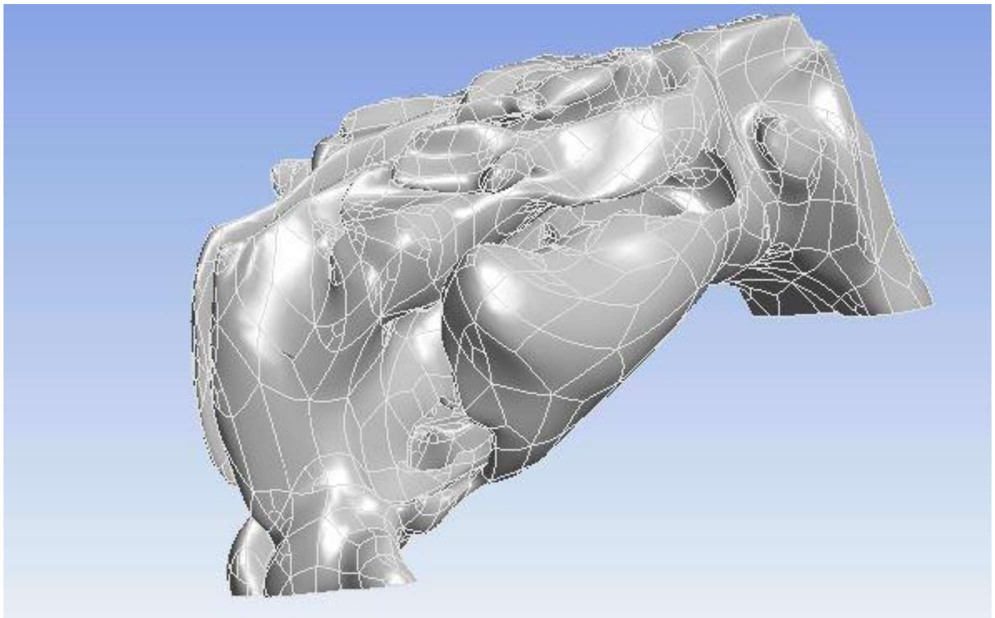


Figure 9 3D Model Imported to ANSYS FLUENT

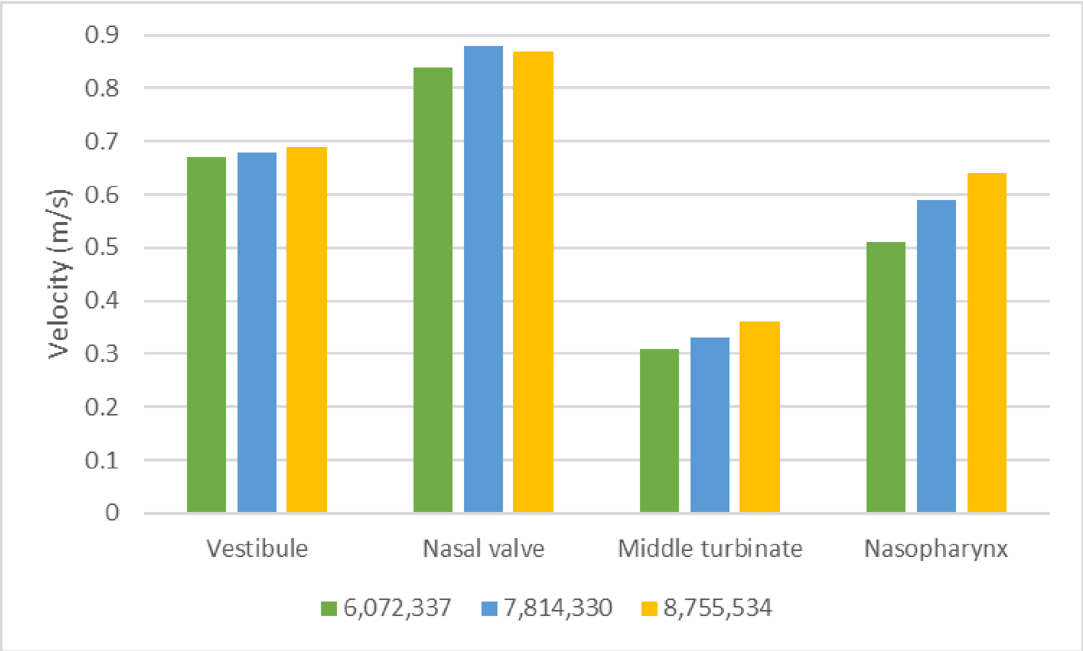


Figure 10 Mesh Dependency Study at Mass Flow Rate 125 mL/s

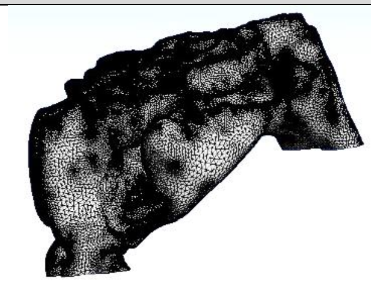
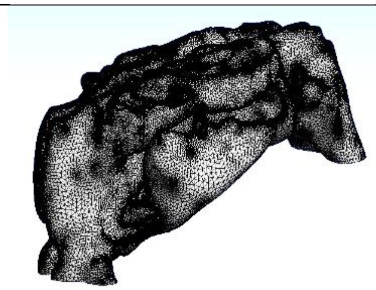
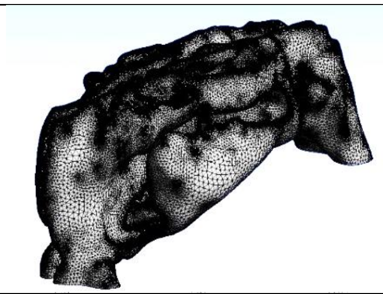
Meshed Model	Meshing Type	Number of Elements
	Coarse	6,072,337
	Medium	7,814,330
	Fine	8,755,534

Table 2 Meshing of Model

The accuracy of the numerical result is closely related to mesh density as well as its distribution. Mesh plays a very significant role in the outcome of numerical simulation [31]. A good mesh must be able to resolve the velocity vectors and effectively capture the fluid properties at all regions inside the nasal cavity [31],[32],[33]. The simulation is being run for the medium meshed model in ANSYS FLUENT after the mesh dependency study. The mesh grip dependency study shows an optimized meshing of 7,814,330 elements. The model is being run for mass flow rate ranging from 100mL/s to 425mL/s for getting accurate result. As the inspiratory flow rate for healthy adults is ranged between 80 - 200 mL/s for light breathing and 200 - 660 mL/s for non-normal conditions such as during exercises [34].

CHAPTER 4

RESULT AND DISCUSSION

Results acquired from the simulation are presented and discussed in three sections. The first section is the geometrical comparison of two nasal cavity models, which are the obtained Malaysian female adult patient model and the developed standardized Malaysian female adult model generated by Lee et al. in her previous researches [18]. In this section, the comparison is performed via visual observation on both 3D nasal cavity models and the comparison between the cross-sectional area at different planes. The second part of this study is focused on the pressure at different planes with various mass flow rate of the patient's model, then pressure drop of the nasal model is being discussed at this part as well. The last section involved the comparison of both models, including the velocity magnitude in different plane, as well as the graphical results obtained from the CFD analysis, which is the velocity contour for both models.

4.1 Geometrical Comparison

Respiratory physiology and pathology are strongly dependent on the airflow inside the nasal cavity. Since nasal airflow is heavily affected by the geometry of the flow passage, changes in the anatomical shape of the nasal cavity, due to diseases or surgical treatments, alter the nasal resistance and functions of nose [35]. The paranasal sinuses are not taking into consideration as only airflow of nasal cavity is being studied in this research [18],[24]. Geometric configuration plays a significant role in the flow distribution inside the nasal cavity especially for disease case as the imbalance of the nasal cavity due to septal deviation is thought to be a typical etiology of nasal airway obstruction [36],[13],[7],[4]. The virtual geometry comparison 3D models are shown in Table 3 below.

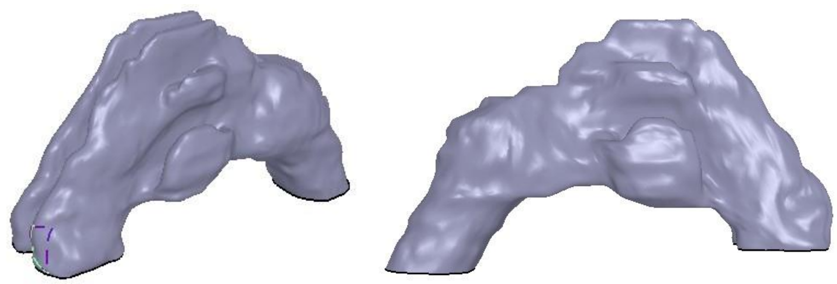
Nasal Model	3D Geometry
Female Adult Patient with Septal Deviation and Allergy Rhinitis	
Standardized Female Adult by Lee et al. [18]	

Table 3 Geometrical Comparison for Both 3D Model

From Table 3 above, the patient's nasal cavity model has a lot of disconnections that will lead to difficulties in breathing [12],[15]. The cross section on the middle turbinate is much different in size as well, the standardized model has smooth and clean airway compared to patient's model. Patient's model has lots of creases on surface as there is a lot of growths in nasal airway due to allergy rhinitis [9],[37],[38].

To make a better comparison, both models have compared the cross-sectional area at 4 different planes, which are vestibule, nasal valve, middle turbinate and nasopharynx. The cutting planes for both models are shown in Figure 11 below. However, the cutting planes are difficult to be at same positions as different nasal cavity models have different sizing, therefore there is a pattern to the error vectors in contours. Considering the spacing between planes, this represents a large velocity gradient in the out-of-plane dimension. Consequently, even a small out-of-plane translation of the model would result in the observed error [21].

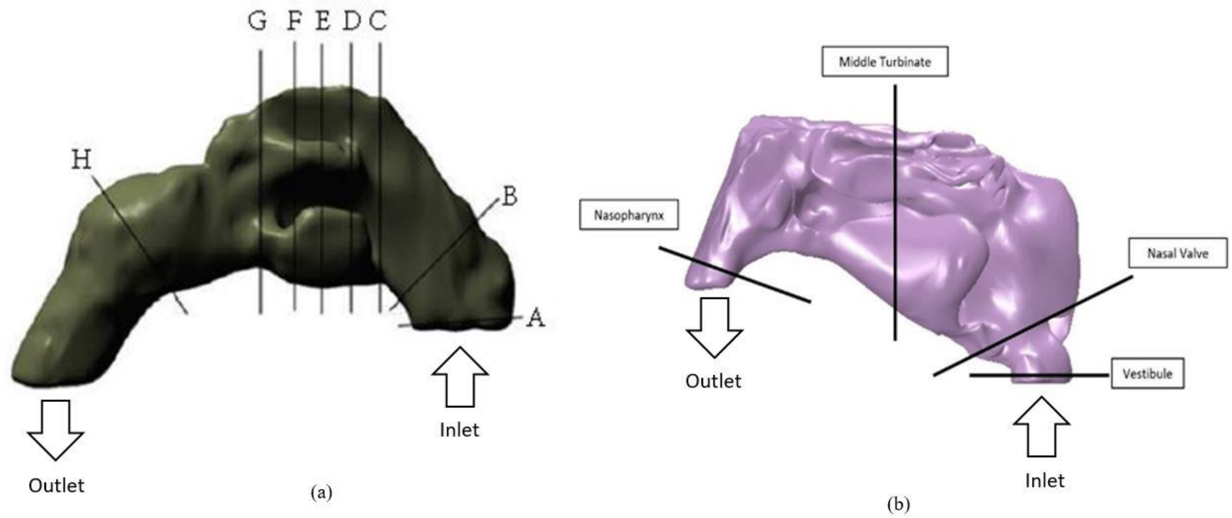


Figure 11 Cutting Planes for Both Models: (a) Standardized Model from Lee et al. (A=vestibule; B=nasal valve; E=middle turbinate; H=nasopharynx); (b) Patient's Model

To show the differences caused by septal deviation and allergy rhinitis, the cross-sectional area at different planes of both models are being compared and shown in Table 4 and Figure 12 below.

Plane	Cross-sectional Area (cm^2)		
	Patient's Model	Standardized Model by Lee et al. [18]	Percentage Different
Inlet	0.15066816	0.34872949	57%
Vestibule	0.15388511	0.35425289	57%
Nasal valve	0.13621432	0.29106226	53%
Middle turbinate	0.26335791	0.64515747	59%
Nasopharynx	0.19838503	0.54266273	63%
Outlet	0.16834382	0.35474969	53%
Average	0.178475725	0.422769088	58%

Table 4 Comparison between Cross-sectional Area at Different Planes for Both Models

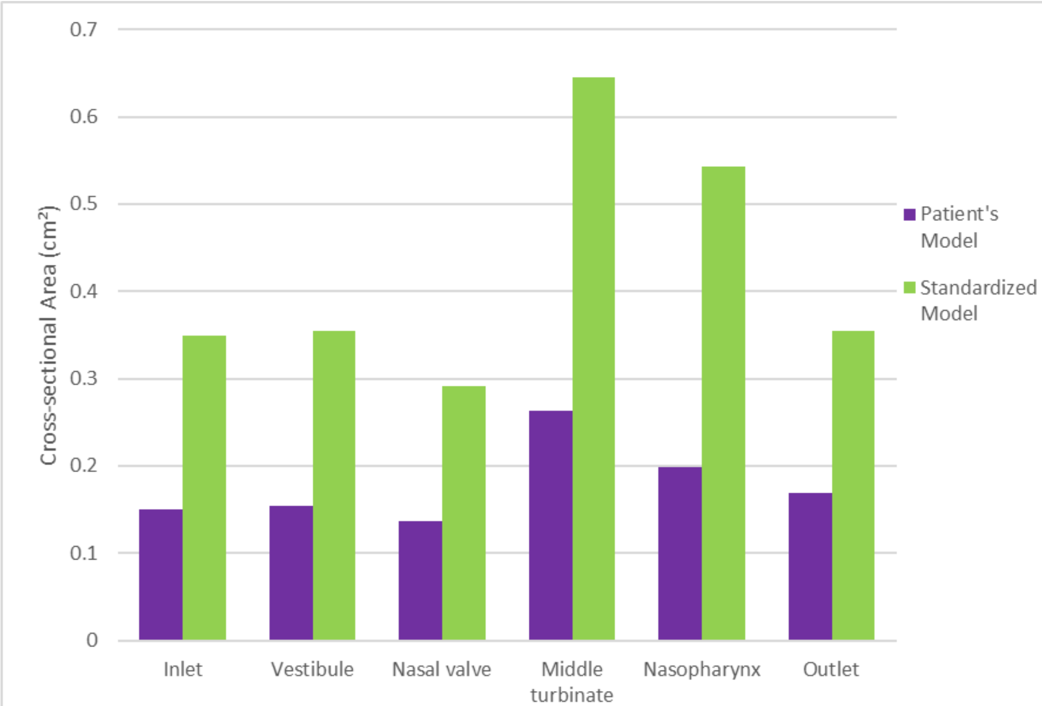


Figure 12 Comparison between Cross-sectional Area at Different Planes for Both Models

It is obvious that the standardized model by Lee et al. [18] has overall higher cross-sectional area that the patient's model. The patient's model has averagely 58% smaller than the standardized model. The percentage differences at each plane ranged between 53% to 63%, which shows the patient's model has smaller size constantly compared to the standardized model caused by the growths in the nasal airway. From Figure 12, both models have same trend of cross-sectional area, both models have the smallest cross-sectional area at nasal valve and the largest cross-sectional area at middle turbinate. Therefore, if there is any surgery needed for this patient, the surgery is suggested to do on plane having biggest percentage different, which is nasopharynx. To have a clear figure on the obvious different between both models, volume of the model is calculated as well. The volume of patient's model is 23.71cm^3 while the standardized model has volume of 45.23cm^3. Patient's model has 48% less volume than the standardized model. The results of cross-sectional area and volume are quite similar as the patient's model is about half smaller than the standardized model.

4.2 Pressure

Understanding of the mechanism of the breathing is important for the prevention of the diseases and also for determine the method of the treatment that can cure these diseases [19],[39]. In research studies, airway pressures are frequently measured as the pressure was described as a function of time at the exit of the domain [39],[40]. Therefore, the computational analysis is performed for the patient's 3D nasal model and the pressure drop is calculated for mass flow rate ranging from 100 mL/s to 425 mL/s. The pressure obtained for this part is the relative pressure to the atmospheric pressure, negative pressure indicates human breath with pressure lower than atmospheric pressure. The pressure drop across nasal cavity from the model inlet to outlet is obtained and shown in Figure 13 below.

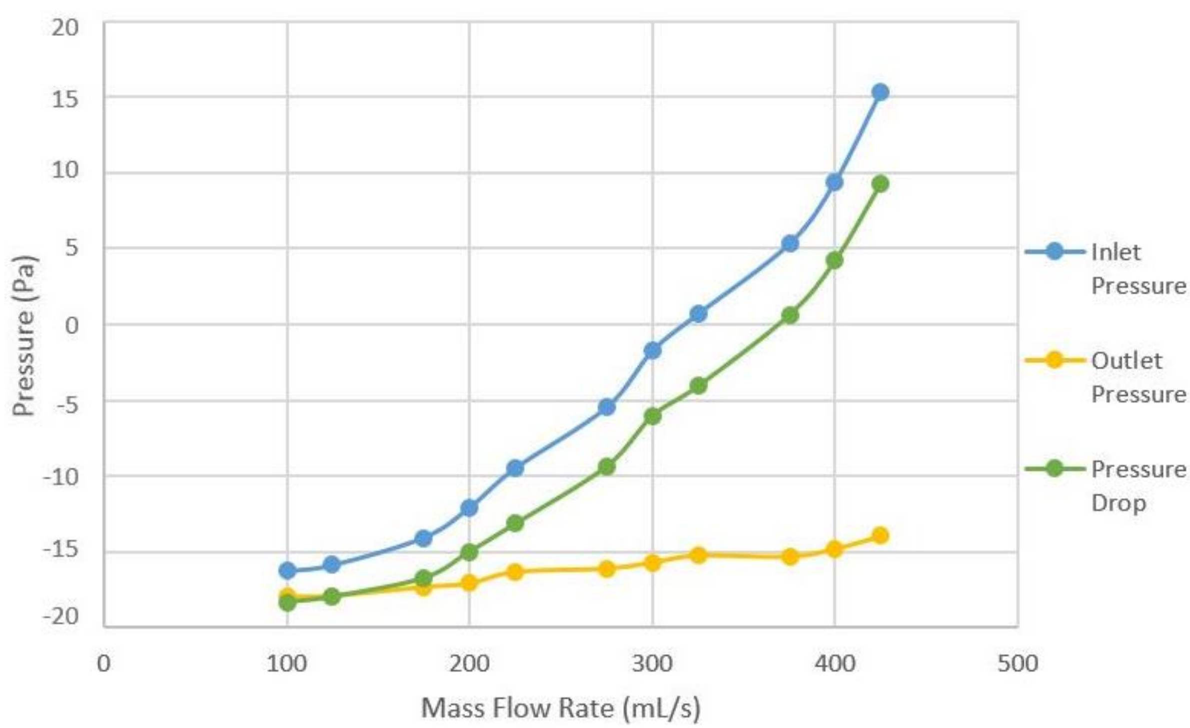


Figure 13 Graph of Pressure Drop against Mass Flow Rate

The inlet pressure has dramatically increases as the mass flow rate increases, while the outlet pressure remains constantly at different mass flow rate. From the graph, it can be clearly seen that the pressure drop increase gradually as the mass flow rate increase. Difference in pressure induces different local flow rate and wall shear stress distributions, this is the reason leads to different local dynamics [40],[41]. To see the pressure change throughout the whole nasal airway, the pressure at different planes on different mass flow rate is shown in Figure 14 below.

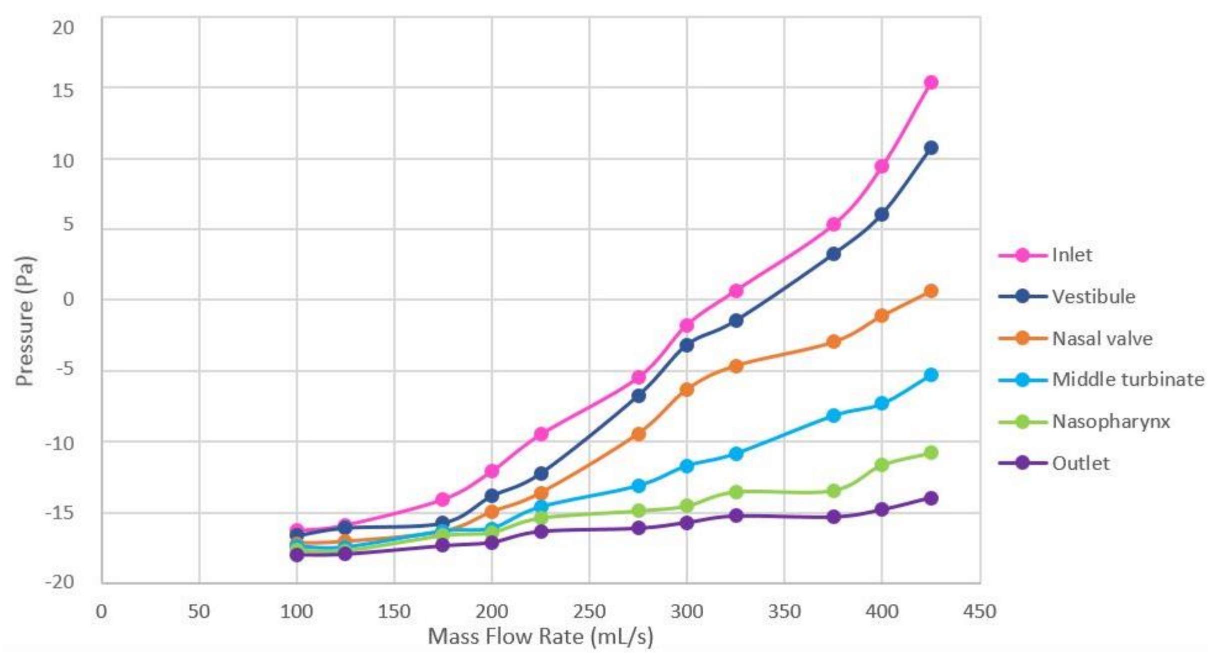
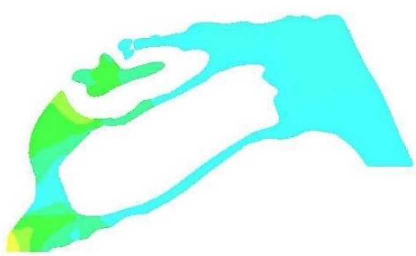
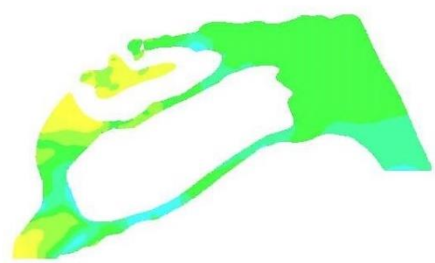


Figure 14 Pressure on Different Planes at Different Mass Flow Rate

From the graph, it is clear that pressure drops gradually throughout the nasal airway due to the wall shear stress [40],[41]. The wall shear stresses during inspiration are predominantly higher in the anterior region [42]. The maximum wall shear stress obtained The pressure change increase dramatically after 250mL/s of mass flow rate as some researchers declared that mass flow rate less than 250mL/s is defined as laminar airflow while mass flow rate with more than 250mL/s is considered as turbulent airflow [43],[42],[26],[44]. Pressure drop is caused by the resistance of the airways. Airways resistance is the opposition to flow caused by the friction forces. It is defined as the ratio of driving pressure to the rate of air flow. Resistance to flow in the airways depends on whether the flow is laminar or turbulent, on the dimensions of the airway and on the viscosity of the gas [19]. Thus, the pressure drops climactically at the turbulent flow. Thus, it proved that there is a significant pressure drop at turbulent flow compared to laminar flow. At same flow rate, it is also obvious that the pressure keeps dropping from inlet to outlet. Inlet pressure always highest then follow by vestibule, nasal valve, middle turbinate, nasopharynx finally the nasal outlet with the lowest pressure. The pressure contour from side view below shows the pressure distribution for both laminar and turbulent flow.

Mass Flow Rate	125mL/s	400mL/s
Type of Flow	Laminar	Turbulent
Side View Pressure Contour		

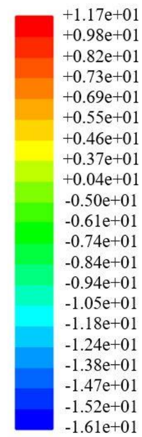


Table 5 Side View Pressure Contour for Both Laminar and Turbulent Flow

4.3 Velocity

Velocity magnitude between patient's model and standardized model from Lee et al. [18] at different planes are being compared. From the comparison, the impact of septal deviation and allergy rhinitis on human nasal airflow can be shown clearly. The models' velocity magnitude at same mass flow rate, which is 125mL/s is tabulated in table with percentage different and plotted as graph to show the velocity behaviour of patient's model. The results are shown in Table 6 and Figure 15 below.

Planes	Velocity Magnitude (m/s)		
	Patient's Model	Standardized Model by Lee et al. [18]	Percentage Different
Inlet	0.796214	0.38773257	-105%
Vestibule	0.675221	0.35802209	-89%
Nasal valve	0.880186	0.42031079	-109%
Middle turbinate	0.331966	0.19572208	-70%
Nasopharynx	0.589943	0.25819995	-128%
Outlet	0.642273	0.35236112	-82%
Average	0.652633833	0.328724767	-99%

Table 6 Comparison between Velocity Magnitude at Different Planes for Both Models at 125mL/s

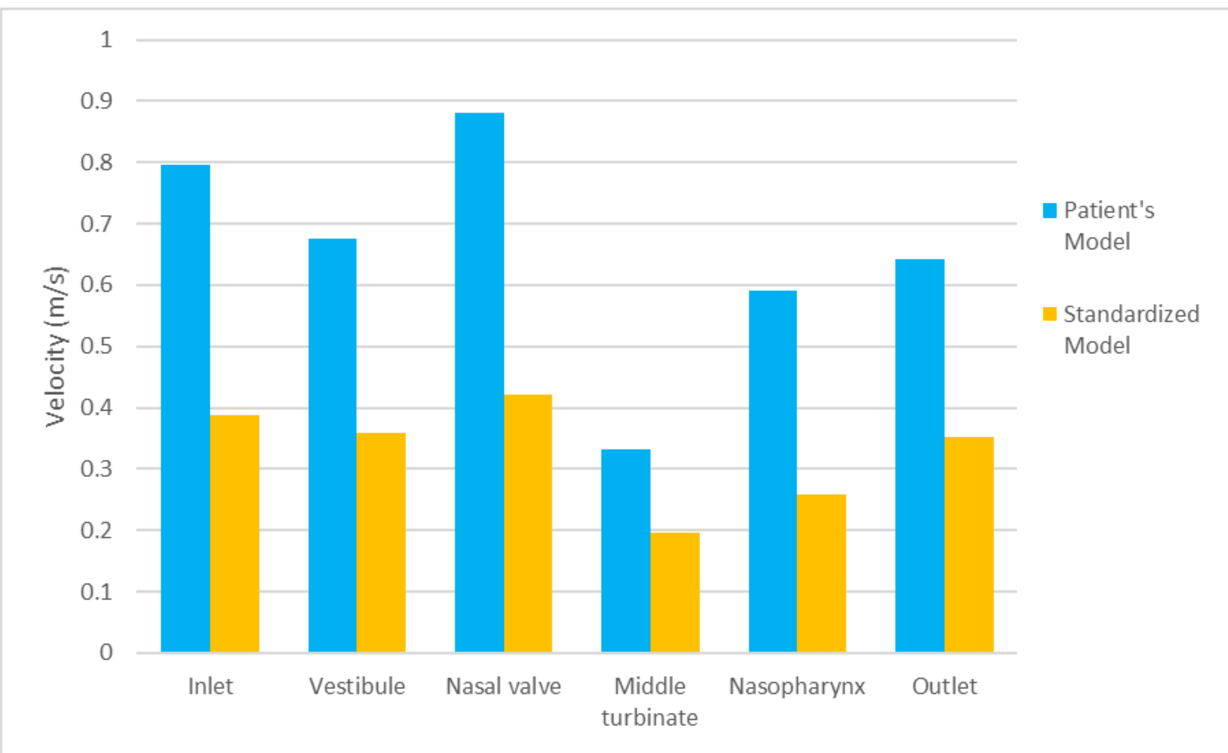


Figure 15 Comparison between Velocity Magnitude at Different Planes for Both Models at 125mL/s