EFFECT OF FUNCTIONAL ENDOSCOPIC SINUS SURGERY TO THE FLOW BEHAVIOR IN NASAL DURING RESTING BREATHING CONDITION

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ABSTRACT

Functional endoscopic sinus surgery (FESS) is a surgery to remove uncinate process in order to restore sufficient sinus ventilation and drainage in nasal. However, there were a few cases with side effects such as facial pain, reduction in sense of smell and sinusitis reoccurrence of infection. In this study, the effect of uncinate process removal is investigated. Images of the model were done through computational technique and then the flow was simulated to predict the effect of the removal. Inhalation processes with resting breathing condition were modeled. The results show that smooth flow was observed at nasal area which indicates successful surgical process. However for post FESS model the result shows that the possibilities of sinusitis reoccurrence of infection were high. Finally, velocity profile in the olfactory area show non-favorable flow condition for effective smell senses.

KEYWORDS*: Nasal; Paranasal Sinuses; FESS; Flow behavior; 3D actual model.*

1.0 INTRODUCTION

Functional Endoscopic Sinus Surgery (FESS) is a surgical treatment for patients suffering from chronic sinusitis infection who have not improved with medical treatment. Basically, FESS is a minimally invasive technique to remove the uncinate process as shown in FIGURE 1, with the intention to restore sufficient sinus ventilation. Robert [1] reported that most of the study shows 80% to 90% rates of post surgery success, however for patients with chronic allergic sinusitis the result shows lower percentage. However, there were a few cases with side effects such as facial pain, reduction in sense of smell and sinusitis reoccurrence of infection. The removal of uncinate process exposes operated paranasal cavity to contaminated inhaled air flow that leads to allergen exposure to a larger surface area and causes increased mucosal disease [2].

Nowadays, Computational Fluid Dynamics (CFD) methods are extensively used in science and industry with the intention to design, to optimize products and to simulate natural processes, including numerous biomedical applications. CFD methods were applied to simulate nasal air flow to increase the understanding of the detailed flow characteristic inside the human nasal cavity without any intervention and clinical risk for the patient.

The air flow field has been studied with both experimental models and numerical models over the years and are imaged with either computed tomography (CT) or magnetic resonance imaging (MRI). Even though anatomically precise nasal models can be obtained, it is extremely difficult to obtain measurements from the small and complicated nasal models. In order to overcome these problems, some researchers, constructed scaled-up physical models, Scherer et al.[3] studied airflow with a three times enlarged plastic model of a half-nasal cavity based on MRI data while Hahn et al. [4] used a 20 times enlarged model of a healthy right human adult nasal cavity constructed from CT scans to study airflow patterns.

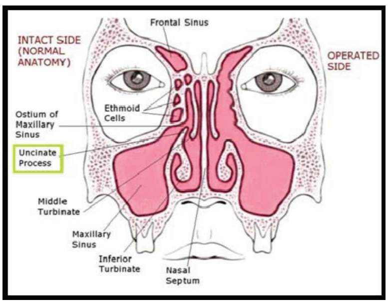


FIGURE 1
Nasal anatomy for pre and post FESS(coronal view)

Air flow velocity near the wall and wall shear stress are important quantities in relation to many physiological processes, such as pressure drop through the nose, particle deposition and exchange processes at the wall [5]. Hahn *et.al.*

found that increasing of nasal air flow velocity at a constant inlet concentration resulted increasing of total olfactory uptake for all odorants as well. The convective diffusion transport of odorants from ambient air to the mucus lining of the nasal cavity depends on several variables such as anatomy of the nose, velocity field in the airways, diffusivity of odorants in air and mucus, solubility of odorants in mucus and the thickness of the mucus layer [6]. J.wen found that air flow patterns are sensitive to the geometric construction within the human nasal cavity.

In this paper, we present a highly automated technique for constructing numerical models of a human nasal in particular the sinuses from CT scan data. Three numerical models of human nasal cavities and sinuses are developed with this automatic technique, and airflow was simulated with a commercially-available EFD Lab software package.

2.0 METHODOLOGY

A. Nasal Anatomy

Nasal cavity is the area between nose tip and throat as shown in FIGURE 2, through which air flows during respiration. The variable surfaces in nasal cavity composed of tissue, bone and hair. Swirling and turbulence, which affects the airflow pattern, occur due to the rough surfaces in nasal cavity. The cross-sectional area of the nasal cavity gradually decreases throughout the nasal valves, up to the internal valve, where the cross section is unlike the rest of the nasal cavity that referred to as turbinate. After the turbinate, the separate passages of airflow rejoin and enter the nasopharynx, the final region of the nasal cavity. The cross-sectional area of the nasal cavity in the nasopharynx is greater than in the turbinate and so it is not considered the cause of airflow restrictions. The turbinate redirect air into certain nasal passages depending on its function [2].

The nasal cavity contains the smell organs as well as providing passageway for air during respiration. From fluid mechanics point of view, the airway nasal is designed to reduce airflow resistance in nasal passage to allow easy breathing. The extension of the inferior and middle turbinate with the septum create a large surface area and its curly structure cause swirling and turbulence during breathing, which affects airflow [5].

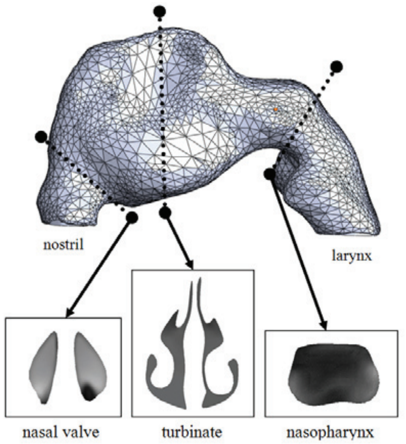


FIGURE 2
Nasal cavity anatomy

Paranasal sinuses are air-filled spaces, communicating with the nasal cavity, within the bones of the skull and face as shown in FIGURE 3. According to the bones within which the sinuses lie, paranasal sinuses are divided into four subgroups that are named maxillary, frontal, sphenoidal and ethmoidal sinuses. The maxillary sinuses are the largest of the paranasal sinuses and are located under the eyes, in the maxillary bones. The frontal sinuses which is forms the hard part of the forehead while the ethmoid sinuses, which are formed from several discrete air cells within the ethmoid bone between the nose and the eyes . [7]

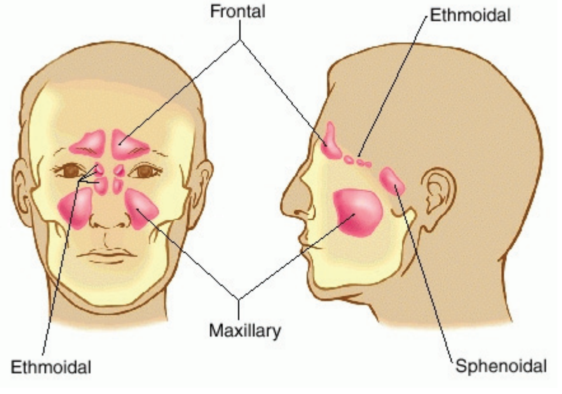


FIGURE 3
Paranasal sinuses anatomy (coronal and sagittal view)

B. Three Dimensional Actual Model Reconstruction

The nasal cavity geometry was obtained through a CT scan of the nose of a healthy 34-year old, Asian male as shown in FIGURE.2. The CT scan was performed using a SIEMEN Body Scanner. The recorded pixel size is 0.6328 pixels while the resolution of the CT scan is 512. The scans captured outlined slices in the *X–Y* plane at different positions along the Z-axis from the entrance of the nasal cavity to just anterior of the larynx at intervals of 1 mm to 5 mm depending on the complexity of the anatomy. The focus area of this study was as in white box in FIGURE 4 as shown below.

The successful scanned images were transferred electronically to CT scan conversion software called AMIRA 5.2.2. The next step was threshold to capture various individual regions in CT scan slice. Then the slices images were undergoing '*calculate in 3D*' operation and will be edited under 'edit mask in 3d' operation.

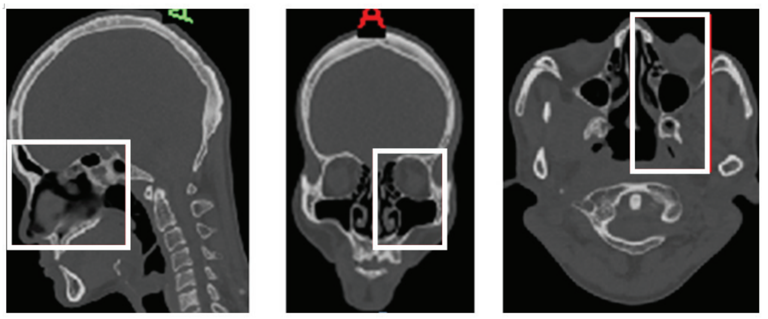


FIGURE 4
Nasal cavity and paranasal anatomy(coronal,sagittal and transverse view)

Under Morphology operations the model was dilated. The anatomical wall was successfully generated around the 3D model by using Boorlean operations. The generated model was then transferred to another software package called MAGICS 13 to make major modification such as holes patching, geometry correction and volume reconstruction. In order to reduce number of faces, the model then transferred back to AMIRA to fit in the SOLID WORK 2008. Finally, the three-dimensional computer model was completed and it saves as STL format for flow analysis purpose. The summary of this process was shown in FIGURE .5.

There are three major actual 3D models generated in this study which are healthy, post FESS minor and major as shown in FIGURE 6. Post FESS minor is based on FESS surgery with uncinate process removal only, while in post FESS major model the removal process include some part of the paranasal sinuses and uncinate process. TABLE 1 shows the removal part and percentage of airway increment in each model.

TABLE 1
Model removal part

Model	Removal part	Airway increment (%)
Healthy	None	None
Post FESS minor	Uncinate process	0.19
Post FESS major	Uncinate process and sinuses	0.44

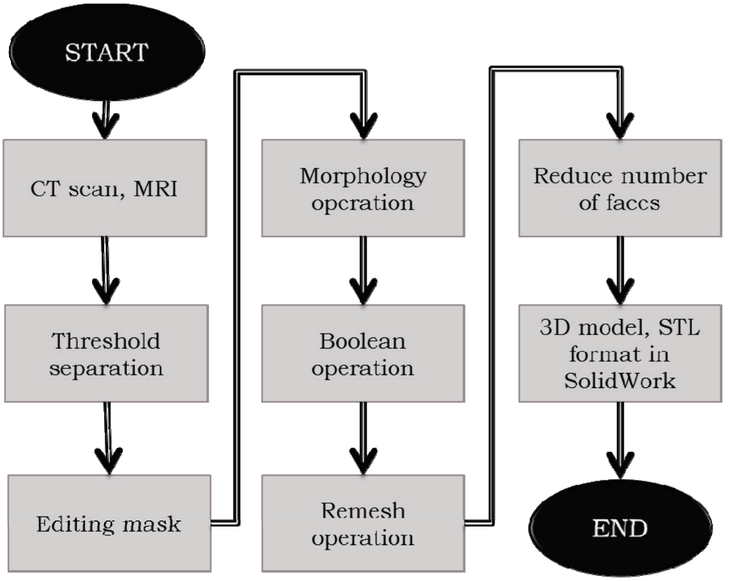
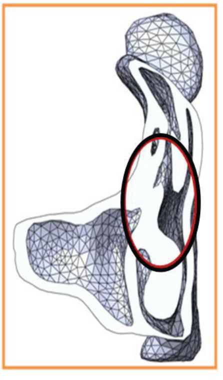
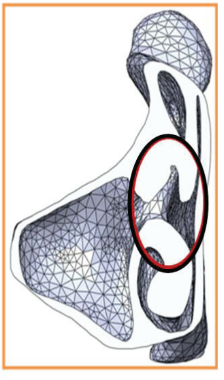
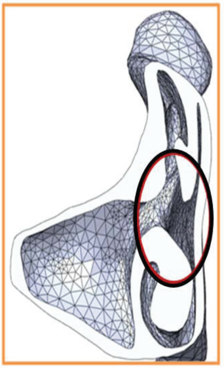


FIGURE 5
Model reconstruction process flowchart

TABLE 2
Healthy, post FESS minor and post FESS major actual 3D models

Type of model	Healthy	Post FESS minor	Post FESS major
Coronal view			

C. Boundary Condition

As the velocities were less than the speed of sound, the flow in the nasal cavity and sinuses assumed in incompressible flow condition [8]. In this study, the flow was also considered laminar and turbulent. The model exterior wall boundary conditions were assumed to be rigid. While at the interface between air and the surface of the nasal cavity and sinuses, the no-slip boundary condition was defined. The simulation was performed only for inspiration phase, as the structure of the nasal cavity and sinuses are not constant during both inspiration and expiration. The air flow rate was set according to adult breathing condition for exercise breathing condition 5 L/min. The boundary condition at the inlet was set as ambient pressure, 1 atm and the air at 310 K. The temperature of the rigid wall of nasal cavity was assumed average of the temperature along the structure of the nasal cavity to be 305 K, [7].

D. Numerical Method

All graphical manipulation was done using Solid Works 2008 software and EFD Lab. The processed geometry or 3D model was saved as a Stereo Lithography file (STL) and then was exported to the CFD package EFD, which allows the STL file to be converted from a wall fabricated hollow model into a volume filled with tetrahedral cells, of 0.1mm edge length. The volume mesh is comparable to the numerical solution of the fluid flow. Using EFD, the boundary conditions were applied to both inlet and outlet of the 3D model. By using the same software, flow velocity in the nasal 3D model was calculated by solving the Navies-Strokes equations that govern 3D flow in incompressible fluids assumptions. The model was set up as a rigid, non slip with zero velocity walled, steady state model as stated in the boundary condition section.

3.0 RESULTS AND DISCUSSION

Simulation results from Engineering Fluid Dynamics (EFD) on all of three models were based on the CT scan data. The purpose of this study was to analyze the effect of FESS surgery by using different model which were healthy model, post FESS minor and post FESS major in term of air flow characteristic which was flow velocity in human nasal airways. The simulation results were performed during resting breathing condition which was 5 L/min of air.

E. Velocity Distribution

The model in FIGURE 7 shows the inlet (nostril) and outlet (nasopharynx) boundary during inhalation. The line indicated in this model shows the flow trajectory that reflected the velocity distribution in FIGURE 8. The line was exactly at the center of nasal valve, middle turbinate and nasopharynx. Instead of inferior and superior turbinate, middle turbinate was chosen because it was directly connected to paranasal sinuses and this was the focus area in this study.

Generally, the graph in FIGURE 8 showed that from 0 to 1.0 non-dimensional distance (nostril to nasopharynx) the velocity increased as the flow go through the nasal valve. The velocity decrease for a while and kept increasing until reaches the highest peak throughout the nasal cavity, later the velocity start to abruptly decrease immediately after leaving nasal valve. These phenomena are corresponding to expanding in cross section area at the anterior turbinate to accommodate the olfactory sensors and the turbinate bone projections. Finally, air flow become stable at the nasopharynx where the airflow in both left and right nasal cavity join before enter the trachea region.

The air flow velocity in pre FESS model is higher compared to the post FESS model and the graph shape (FIGURE 8) were generally similar to each other. However, these phenomena changes as the flow reach the operated area (indicated in dotted box in FIGURE 8). The velocity distribution in pre FESS model was stable and totally different from both post FESS model. This occurred due to the increment in cross sectional area in nasal for both post FESS.

Finally, the velocity reduce and reach at same point for post FESS model while for pre FESS the velocity was higher compare to the others at non dimensional distance 1.0. At this section velocity were low in order to prepare the flow before it enter the trachea. High velocity at trachea will cause damage to vocal cord.

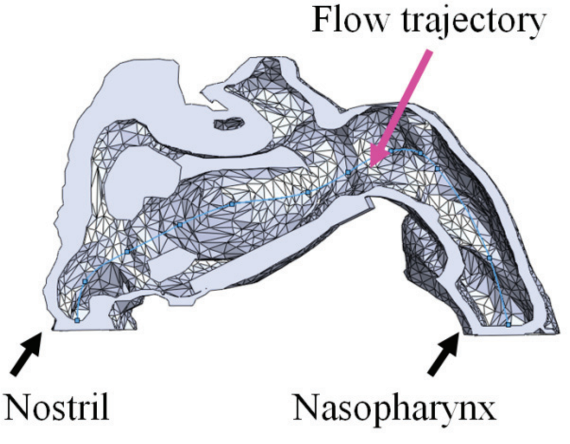


FIGURE7
Nasal cavity and paranasal anatomy (sagital view)

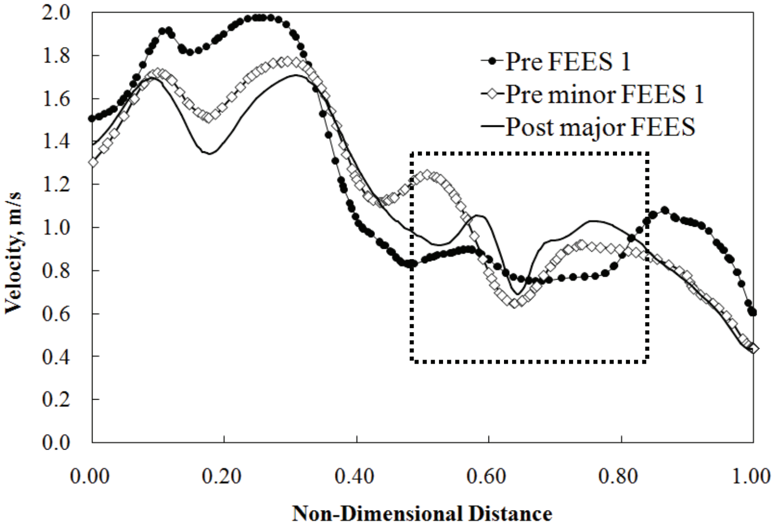


FIGURE 8
Nasal cavity and paranasal anatomy

F. Particle Flow Trajectory

The 3D nasal model in FIGURE.9 indicates the inlet and outlet boundary during inhalation of the nasal airway. The range for particle fluid trajectory for velocity during flow rate 5 L/min was as shown in FIGURE.9. The range in FIGURE.9 shows that the lowest velocity at flow rates 5 L/min was 0 m/s and the highest velocity range at all flow rate was 4.31272 m/s.

1) Olfactory Region

Fluid particle trajectory for velocity during inhalation in healthy, post minor FESS and post major FESS model during flow rate 5 L/min, were shown in FIGURE 10, FIGURE 11 and FIGURE 12. Generally, the air flow velocity during inhale decrease as the distance from nostril increase, due to the increment in flow resistance caused by the changes in nasal cavity structure and gradual increment in nasal cavity cross-sectional area throughout the nasal.

The comparison velocity in nasal valve at all model were quite similar to each other. On the other hand, when the flow reach uncinate process velocity in post major FESS was the highest and this increment in velocity cause by the uncinate process removal at nasal cavity in post FESS major that increase the cross section area. As the flow enters the nasopharynx parts, the velocity in each model was quite similar to each other. From the results, the velocity at olfactory region was highest in healthy model meanwhile the lowest velocity was in post FESS major. This shows that the sense of smell will reduce as the odorants uptake in olfactory region reduce due to the decrement in velocity.

2) Paranasal Sinuses

Healthy model in FIGURE 10 shows that inhaled air do not enter the paranasal sinuses which was similar to clinical study done by Nayak [6]. However, results in post FESS minor shows that inhaled air enter only maxillary sinus (13%), while in post FESS major the inhaled air enter both maxillary sinus(11%of inhaled air) and frontal sinus (2%of inhaled air).

Air flow velocities that go through maxillary sinuses were higher in post FESS major compared to the post FESS minor model. The air flow through frontal sinuses percentage was too small compared to flow percentage that enter maxillary sinuses.

In healthy nasal, the air flow through paranasal sinuses only during exhalation due to the changes of uncinate process position within inhalation and exhalation. Uncinate process act as border that protect the paranasal sinuses from contaminated inhale air during respiration and allows sterilize exhaled air into the paranasal sinuses during exhaled. The uncinate process removal in both post FESS will exposed the paranasal sinuses to contaminated inhaled air, then the paranasal sinuses will get infected easily.

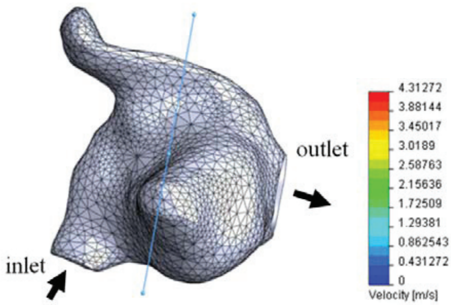


FIGURE .9
Nasal 3D model and velocity range

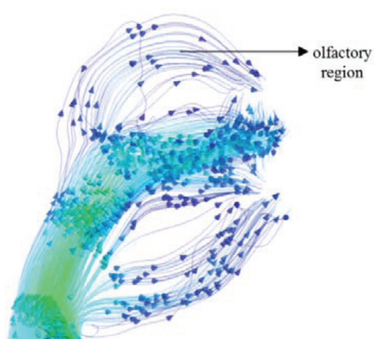


FIGURE 10
Fluid particle trajectories for healthy model

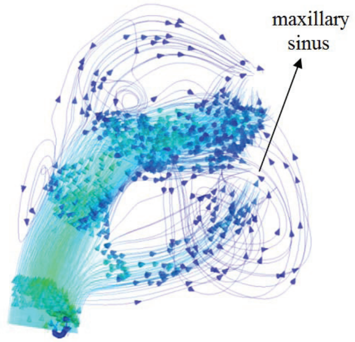


FIGURE 11
Fluid particle trajectories for post FESS minor

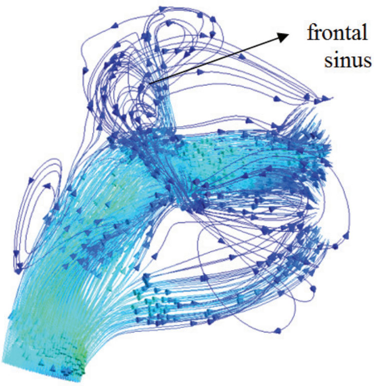


FIGURE 12
Fluid particle trajectories for post FESS major

4.0 CONCLUSIONS

The air flow characteristic of specific geometry from human nasal airway from CT scan image was numerically studied by using the EFD software. The air flow velocity through the nostril to nasopharynx was examining three different models that represent healthy and post FESS minor and major models specifically.

Generally, the results obtain in fluid particle trajectory in all models show that the air flow velocity during inhale for all flow rates were decrease as the distance from nostril increase. The increment in flow resistance causes the changes in nasal cavity structure and the gradual increment in nasal cavity cross-sectional area throughout the nasal valves, turbinate and nasopharynx. Small changes in nasal structure or cross section area will also change the flow pattern and characteristic as well.

In healthy nasal, the air flow through paranasal sinuses only during exhalation due to the changes of uncinate process position within respiration process. Either minor or major post FESS will be exposed the paranasal sinuses to contaminated inhaled air. Therefore, the paranasal sinuses will get infected easily because of removing the uncinate process

The velocity at olfactory region were highest in healthy model meanwhile the lowest velocity were in post major FESS. This shows that the sense of smell will reduce as the odorants uptake in olfactory region reduce due to the decrement in velocity.

The finding in this study will be valuable to known as ear, nose and throat (ENT) field. With these results, preliminary study on optimum part (uncinate process and paranasal sinuses) to remove during the surgery (FESS) will be identified. Moreover, this could restore sufficient ventilation system in human nasal. Reduction on surgery side effect such as facial pain, reduction in sense of smell and headache could be known from this research.

5.0 ACKNOWLEDGMENT

This research was supported by grant number 79415 from the Faculty of Medical Engineering and Health Science of Universiti Teknologi Malaysia

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