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COMPUTATIONAL FLUID DYNAMICS STUDY OF AIRFLOW AND PARTICLE DEPOSITION IN DISEASED NASAL AIRWAY

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By

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
AR	Acoustic Rhinometry
AAR	Active Anterior Rhinometry
BMI	Body Mass Index
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CPAP	Continuous Positive Airway Pressure
CT	Computed Tomography
DE	Deposition Efficiency
DF	Deposition Fraction
DICOM	Digital Imaging and Communications in Medicine
DPM	Discrete Phase Modeling
DSE	Digitized Shape Editor
ENT	Ear Nose and Throat
EPA	Environmental Protection Agency
FESS	Functional Endoscopic Sinus Surgery
FSI	Fluid Structure Interaction
HU	Hounsfield Units
IGES	Initial Graphics Exchange Specification
LES	Large Eddy Simulation
LRN	Low Reynolds Number

MAS	Mandibular Advancement Splint
MMA	Middle Meatal Anstrostomy
MRI	Magnetic Resonance Image
NA	Not Available
NAR	Nasal Airway Resistance
OSA	Obstructive Sleep Apnea
PIV	Particle Image Velocimetry
RANS	Reynolds Averaged Navier Stokes
SST	Shear Stress Transport
UPPP	Uvulapalatopharyngoplasty
US	United States
USM	Universiti Sains Malaysia

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2. **V.N. Riazuddin**, K. A. Ahmad, M. Zubair, M. Tamagawa, N.H.A. Rashid, N. Mazlan, Numerical simulation of airflow in diseased human nasal airway, Mechanical Engineering Research Day 2017 (MERD 2017), Universiti Teknikal Malaysia Melaka, Malaysia (30 March 2017).
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ABSTRACT

COMPUTATIONAL FLUID DYNAMICS STUDY OF AIRFLOW AND PARTICLE DEPOSITION IN DISEASED NASAL AIRWAY

Understanding the properties of airflow in the nasal cavity is very important in determining the nasal physiology and in diagnosis of various anomalies associated with the nose. The complex anatomy of the nasal cavity has proven to be a significant obstacle in the understanding of nasal obstructive disorders. Due to their non-invasiveness, Computational Fluid Dynamics (CFD) has now been utilized to assess the effects of surgical interventions on nasal morphological changes as well as local breathing airflow characteristics through the upper airway of individual patients. Furthermore, nasal inhalation is a major route of entry into body for airborne pollutions. Therefore, the function of the upper airway to filter out the inhaled toxic particles is considered important. The determination of the total particle filtering efficiency and the precise location of the induced lesion in the upper airway is the first step in understanding the critical factors involved in the pathogenesis of the upper airway injury. The present work involved development of three-dimensional diseased upper airway models from Computed Tomographic (CT) scan images derived from a nasal airway without any nasal diseased and an upper airway which was diagnosed with chronic nasal obstruction and obstructive sleep apnea. Numerical simulation of airflow and transport and deposition of inhaled pollutant through chronic diseased nasal airway, constricted pharyngeal representing Obstructive Sleep Apnea (OSA) and diseased upper airway with OSA for pre- and post-operative cases have been studied. Detailed flow pattern and characteristics for inspiratory airflow for various breathing rates (7.5-40 L/min) were evaluated. Simulation of the particle transport and

deposition of micro-sized particles with particle diameter ranging from 1-40 μm were also investigated. In the first part of this study, the surgical treatment performed in the nasal cavity which include septoplasty, inferior turbinate reduction and partial concha bullosa resection substantially increased nasal volume, which influenced flow partitioning and decreases the pressure drop and flow resistance of the nasal passage. The removal of the obstruction in the nasal airway significantly improve the breathing quality. However, the nasal airway experienced approximately about a 50 % decrease in total particle filtering efficiency after surgery. Therefore, careful consideration should be given to this matter before nasal operation especially for a patient with breathing allergic history. In the second part of this study, the morphology of the constricted pharyngeal representing OSA was found to significantly affect the airflow pattern and the deposition fraction of microparticles. The morphology of the upper airway, the size of the inhaled particle and breathing rate was found significantly affect the total particle deposition efficiency and local deposition fraction in the upper airway. The presented regional deposition fraction may be used in specifying the site of highest possibility for respiratory lesions according to the breathing rate and the size of the inhaled toxic particles. Results obtained from this study can be also used to estimate the location of airway obstruction in upper airway of patient with sleep apnea symptom. In the third part of this study, the surgical conducted procedure has cleared out the obstructions in the nasal airway hence improve the airflow distribution through the upper airway during inhalation process. This study shows that the nasal surgery alone can help improve the breathing quality in the upper airway with OSA. The reduction of the airflow resistance in the nasal cavity affect the pressure distribution in the lower part of the upper airway. Obstruction in the nasal passage and sudden airway expansion in the upper airway increased number of particles trap, recirculated and finally deposited in the airway. Finally, the experimental data obtained from the experimental study utilizing the developed pharyngeal airway further validate the result obtained from the numerical study.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Upper airway which consisted of nasal cavity and pharynx is one of the most important components of human respiratory system. It provides the first line protection for lung by warming and humidifying the inspired air. Upper airway plays an important role to filter out the inhaled air from airborne contaminated particles, bacteria and pathogen. However, the success of upper airway physiological function is highly dependent on the fluid dynamics characteristic of airflow through the airway passage. Hence, better understanding of airflow characteristic and transport and deposition of inhaled particle through the upper airway is essential to understand the physiology of upper airway breathing pattern.

During inhalation, upper airway also plays an important role to filter out the inhaled toxic and contaminated particles from the polluted atmospheric air. Both the fine and coarse particles which enter the breathing airway during inhalation, not only can induce irritation, moreover, with extensive exposure and high concentration of inhaled airborne toxic and infectious particle, the airway is susceptible to chronic injury and could further aggravate upper airway disorder (Harkema *et al*., 2006). Harkema *et al*., (2006) and Grotberg (2001) also reported that the determination of the precise location of the induced lesion in the upper airway is the first step in understanding the critical factors involved in the pathogenesis of the upper airway injury. As we already know that the toxic and contaminated particles could harm and affect the health of the human population. Hence it is important to investigate and improve understanding of the airflow distribution and particle transport and deposition in the human nasal airway. The location of the particle deposition in an airway is important information for correlating inhaled toxins or carcinogens to disease locations and for developing potential therapies.

Airflow through human upper airway has been studied numerically and experimentally by a number researchers (Garcia *et al*., 2007; Kim & Chung, 2004; Mylavarapu *et al*., 2009; Segal *et al*., 2008; Weinhold & Mlynski, 2004; Wen *et al*., 2008; Xiong et al., 2008). Furthermore, several researchers have undertaken studies pertaining to airflow through nasal cavity using measuring devices such as rhinomanometry and acoustic rhinometry (Hilberg *et al*., 1989; Jones & Lancer, 1987; Shelton & Eiser, 1992; Sipila & Suonpaa, 1997; Suzina *et al.*, 2003).

Rhinomanometry is used to measure the pressure required to produce airflow through the nasal airway and acoustic rhinometry is used to measure the cross-sectional area of the airway at various nasal planes. However, measuring the precise velocity of airflow and evaluating the local nasal resistance in every portion of the nasal cavity have proven to be difficult (Ishikawa *et al*., 2009). The anatomical complexity of the nasal cavity makes it difficult for the measurement of nasal resistance. The small sizes of the nasal cavity and its narrow flow passage can cause perturbations in the airflow with any inserted probe. Moreover, the reliability of the result obtained using this device depends on optimal cooperation from the subject, correct instructions from the investigator, and standardized techniques (Kjaergaard *et* *al*., 2009). There are reports of failure rates of between 25 % and 50 % in the subjects examined by rhinomanometry (Austin & Foreman, 1994). Furthermore, direct measurement of the total particle deposition efficiency and local deposition fraction of inhaled contaminated particle in the human upper airway are highly impossible.

Due to the inherent limitations of the available measuring devices, Computational Fluid Dynamics (CFD) has been proposed as a viable alternative. CFD which refers to use of numerical methods to solve the partial differential equation governing the flow of a fluid, is becoming an increasingly popular research tool in fluid dynamics (Basri *et al*., 2016). The non-invasive CFD modelling allows investigation of a wide variety of flow situations and particle deposition through human upper airway. Several researchers have conducted studies on the airflow and particle transport and deposition through the human upper airway by using the CFD simulation technique (Abouali *et al*., 2012; Bahmanzadeh *et al*., 2015; Dastan *et al*., 2014; Ghalati *et al*., 2012; Riazuddin *et al*., 2011).

In the present study, initially the effect of nasal obstruction which include septum deviation, turbinate hypertrophy and concha bullosa were investigated. A comparative study was made between the pre- and post-operative model. The effect of nasal surgery on inhaled particle filtering function was also investigated. In order to improve the understanding of the pathophysiology of the Obstructive Sleep Apnea (OSA) disease, numerical simulation of inspiratory airflow through a constricted pharyngeal section representing OSA symptom was conducted. Studies were carried out for various flow rates of 7.5 L/min, 10 L/min, 20 L/min, 30 L/min and 40 L/min suggesting various breathing rates. Lagrangian particle tracking approach was used to investigate the effect of the constricted pharyngeal section on the deposition rate and deposition patterns of microparticles. Microparticles in the size range of 1-40 μm were injected at the nostril inlet and the particle trajectories and regional deposition fractions of the particles were analyzed.

In order to investigate the effect of chronic nasal obstruction on the upper airway diagnosed with OSA disease, numerical simulation of airflow and aerosol deposition in a realistic human upper airway with chronic nasal airway and obstructive sleep apnea symptom for pre- and post-surgery were performed. Different inhalation rates of steady laminar airflows suggesting low breathing activity were simulated numerically through the upper airway models. The airflow characteristics and breathing resistance were analyzed. Lagrangian trajectory analysis approach was used to examine the transport and deposition of the inhaled microparticles through the upper airways before and after surgery. The focus of the final part of this study is to develop an experimental setup and perform experimental work on a pharyngeal airway model to compare and validate the results obtained from numerical study with that of experiment.

1.2 Problem Statement

Although treatment methods in upper airway surgery have constantly improved over time, due to the narrow and complicated structure of the human nasal airway and anatomical differences between each individual, the prediction of a successful individual therapy remains a challenging task. Hence, further studies are needed to improve the diagnosis method and the quality of the future upper airway surgical treatment. The highly detailed anatomy of the pre- and post-operative morphological upper airway model and information derived from CFD analysis would be able to provide relevant information prior to a surgical intervention and medical treatment. The analyzed data of detailed aerodynamic behavior of the upper airways can be made available to the ENT surgeons so that it can be used to assist them in identifying possible sites of obstruction and direct toward the anatomic site of obstruction for surgical intervention. The location of the particle deposition in an airway can provide important information for correlating inhaled toxins or carcinogens to disease locations and for developing potential therapies. The main outcome will lead to the improvement of the diagnostics methodologies or even improved treatment strategies and outcome.

1.3 Research Objectives

The overall objective of the present study is focused on the investigation of the airflow characteristics and inhaled particle deposition in the diseased human upper airway. The main aims include:

i. To develop a three-dimensional computational model of human nasal airway for pre- and post-operative nasal computational models.
ii. To perform CFD analysis on both the pre- and post-operative diseased nasal airway.
iii. To analyze the impact of abnormal nasal passage on airflow characteristics and aerosol deposition.
iv. To investigate the effect of deformation of the pharyngeal section on the airflow and particle deposition in the human upper airway.

v. To develop experimental setup and perform experimental study to validate the results obtained from the numerical study.

1.4 Scope of Work

This research work was first carried out by procuring Computed Tomography (CT) scan images of the normal and diseased human upper airway. For the normal nasal airway, the CT scan data was provided by a radiologist from the Advanced Medical and Dental Institute, Universiti Sains Malaysia. For the diseased upper airway, the CT scan data was provided by a Head and Neck Surgeon from Hospital Serdang, Malaysia. A research proposal was prepared and submitted to the committee of the Clinical Research Centre and the Medical Research and Ethics Committee, Ministry of Health Malaysia to obtained research approval. The ethical approval letter issued by the committees are as presented in Appendix I and II in this thesis.

A normal nasal cavity of 39-year-old Malaysian female was selected for the normal nasal cavity model whereas a 38-year-old Malaysian male diagnosed with chronic nasal obstruction and prevalence of OSA were selected for this diseased upper airway study. The selected CT scan data were imported into an image processing software, Mimics in order to process the scan images and to generate a realistic three-dimensional computational aided design CAD model of the upper airways. This was then followed by construction of three-dimensional surface geometry by using a Computer Aid Design (CAD) software CATIA.

The 3D surface geometries were imported into GAMBIT, ANSYS ICEM CFD and ANSYS FLUENT Meshing for unstructured and hybrid mesh generation. Numerical simulation of airflow and particle transport and deposition were further carried out by using the available CFD commercial software, ANSYS FLUENT. Numerical inspiratory airflow was simulated for various breathing rates which includes 4, 7.5, 10, 20, 30 and 40 L/min. Particles were injected into the upper airway from the nostril inlet to investigate the transport and deposition in the upper airway. The size of the injected particle includes 1, 5, 10, 20 and 40 µm. Experimental test rig was developed, pharynx experimental model was fabricated, and experimental investigation was conducted to compare and validate the results obtained from the numerical study with that of the experimental results.

1.5 Organization of the Thesis

This thesis includes 9 chapters. The first chapter provides an introduction that review relevant research objectives, and related outlines of the purposes of this study. Chapter 2 presents an in-depth review of the background for the research. The chapter begins with an introduction to the anatomy and physiological function of the human upper airway and is followed by a review of previous studies related to the research. Chapter 3 presents the method used to construct and develop the three-dimensional realistic diseased human upper airway from the CT scan data. Chapter 4 presents the numerical method used to perform CFD simulation of airflow and particle transport and deposition in the upper airway computational model. Chapter 5 presents the numerical investigation on airflow characteristics and particle deposition in diseased nasal cavity having turbinate hypertrophy, concha bullosa, and septum deviation. A comparative study was made between pre- and post-operative model. Chapter 6 presents the computational fluid dynamics study of airflow and micro-particle deposition in a constricted pharyngeal section representing obstructive sleep apnea disease. Chapter 7 presents numerical simulation of airflow and aerosol deposition in realistic human upper airway with obstructive sleep apnea and chronic nasal obstruction for pre- and post-surgery. Chapter 8 presents the method used to develop the pharynx experimental model and the experiment test rig for both pre and post-operative cases. The main aim of this study was to analyze and validate the solutions obtained from numerical study. Finally, Chapter 9 presents the summary of the majors research findings derived from the research studied. Suggestions for future works are also presented in this chapter.

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