THE EFFECT OF TRACHEAL STENOSIS ON AIRFLOW USING NUMERICAL MODELLING

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ABSTRACT

The location and size of tracheal stenosis are among the major factors that contribute significantly to the breathing difficulties. It is crucial to understand the relationship between the two factors. Hence, this study aims to establish correlation between the location and size of the stenosis to the possibility of breathing difficulties. This work used ideal trachea model and realistic trachea model derived from Computed Tomography (CT) scan images. The stenosis was patched to the healthy trachea models at regular locations and sizes as proposed by medical practitioners. All models were then subjected to different steady breathing conditions. The changes in the flow behavior due to the different sizes and locations of the stenosis were then examined to determine the pattern of possible breathing difficulties. The results showed that, during high flow rates, the presence of stenosis was observed to produce moderate (-150 Pa) to severe (-440 Pa) pressure drop as the locations of stenosis moved closer to the bifurcation for both actual and simplified models. Two stages of pressure drop behavior also appeared consistently as the lumen became smaller at all sites. For all cases studied, significant changes in the velocity pattern were observed suggesting distorted flow rates into the bifurcation. The present simulation confirms that the overall flow behavior could be significantly affected if the size of stenosis is more than 60% for location far from the bifurcation region, and at size of 50% for location close to the bifurcation region. The outcomes of this study may help the medical practitioners and researchers to understand how dramatic increase in pressure drops occurs inside the trachea and main bronchi with the presence of stenosis at different location and size.

ABSTRAK

Lokasi dan saiz penyempitan saluran trakea adalah antara faktor utama kepada masalah yang berkaitan dengan sistem pernafasan. Adalah penting untuk memahami secara teliti perkaitan antara kedua-dua faktor ini. Justeru, kajian ini ingin melihat secara mendalam hubungkait antara faktor lokasi dan saiz penyempitan yang menyumbang kepada kemungkinan kesukaran bernafas. Kajian ini menggunakan model trakea yang ideal dan realistik yang dihasilkan daripada imej *Computed Tomography (CT)*. Penyempitan telah dipadankan kepada model trakea yang normal berdasarkan lokasi dan saiz yang lazim berlaku. Kesemua model kemudiannya diletakkan dalam situasi aktiviti pernafasan yang berbeza-beza. Perubahan dalam corak pernafasan akan diperiksa untuk menentukan corak kemungkinan masalah pernafasan yang berlaku. Keputusan menunjukkan bahawa, semasa kadar pernafasan sangat laju, kewujudan penyempitan telah menghasilkan kejatuhan tekanan aliran daripada sederhana (-50 Pa) kepada serius (-440 Pa) apabila lokasi penyempitan berdekatan kawasan *tracheal bifurcation*. Dua peringkat kejatuhan tekanan juga muncul secara konsisten apabila saiz penyempitan dibesarkan. Bagi semua kes yang dikaji, perubahan ketara dalam corak had laju menyebabkan aliran udara menjadi tidak stabil di kawasan *bifurcation*. Kajian simulasi ini mengesahkan bahawa corak kelakuan aliran udara secara keseluruhannya hanya akan terjejas teruk apabila saiz melebihi 60% bagi lokasi yang jauh dari kawasan *bifurcation*, dan pada saiz 50% atau lokasi dekat kawasan *bifurcation*. Hasil kajian ini boleh membantu pengamal perubatan dan penyelidik memahami bagaimana dramatiknya penurunan tekanan udara di dalam saluran pernafasan dengan kehadiran penyempitan.

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LIST OF ABBREVIATION

CT	Computed Tomography
MRI	Magnetic Resonance Imaging
DICOM	Digital Imaging and Communications in Medicine
CFD	Computational Fluid Dynamics
U, V	Velocity
P	Pressure
ρ	Density
μ	Viscosity
Re	Reynolds number
D	Diameter
L	Length
lit/min	Liter/minute
m/s	Meter/second
Q	Volume flow rate
t	Time
U	Mean velocity
Re	Reynolds number
L/L_o	Dimensionless length
P/P_o	Dimensionless pressure
V/V_o	Dimensionless velocity

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Stenosis in a human trachea will obstruct the airflow from moving, deep down, to the lungs. The narrowing is often caused by irritation and scarring to the lining of trachea lumen (inside trachea). Symptoms can be the shortness of breathing, dyspnea, brassy cough, recurrent pneumonitis, wheezing, stridor and cyanosis. All these symptoms finally can be attributed to the most chronic and serious disease in respiratory system, asthma. In 2005, World Health Organization (WHO) reported that more than 300 million people around the world suffered from asthma and almost 255 000 patient died accordingly.

Although, there are a variety of methods exist that may be used for evaluation and treatment of tracheal stenosis, it is still not sufficient to support the effort in reducing the numbers of stenosis`s patient. This phenomenon happens because the failure to detect the early signs and symptoms of asthma. Frequently, the signs and symptoms were disregarded or mistaken for variety of other disorders. An effective way to solve this problem is by understanding the airflow moving in and out from the lung to the atmosphere during breathing. Understanding the airflow motion inside the lung can give the medical doctors the early warning on the potential risk of the disease.

The stenosis inside trachea windpipe has three dominant factors; locations of stenosis, degree of stenosis and types of stenosis (Freitag *et al.,* 2007). Each factor will give the significant impact to the airflow motion and increase the level of disease. Almost every asthmatic patient had suffered different dominant factors of stenosis. The signs and symptoms of disease are also dissimilar. Thus, the requirement of airflow analysis is very important to understand the early signs in order to predict the risk in the future. In current practice, clinical diagnosis for the tracheal stenosis suspected such as endoscopic techniques and scanning like Computed Tomography (CT) and Magnetic Resonance Image (MRI) to look inside the obstructive tissues which are relatively inaccurate and followed by further treatment like operation. Medical doctors need to be able to see the blockage from above and below, rather than just looking at a person straight on. This is because a tracheal stenosis is like a thin disk sitting across the windpipe, leaving a small hole in the middle for air to pass through. For sure, there is time for the stenosis increased progressively and finally become worse with asthma before they received proper treatment.

Patients with tracheal stenosis often complaints a relatively sudden occurrence of breathing difficulties, which at the stage of admission to the clinic is observed when loss of 75% or more of the airway lumen has occurred (Schuurmans M.M. *et al.,* 2004). Since most patients with minor stenosis referred for necessary treatment are typically asymptomatic, precise additional information is needed in order to perform proper diagnosis (Spittle and McCluskey, 2000 and Hammer, 2004). Researchers agree that location and size of tracheal stenosis are among major factors that contribute significantly to the possibility of breathing difficulties (McCaffrey *et al.,* 1992).

The effect of stenosis with different sizes to the airflow pattern had attracted several researchers. However, only a few of them had studied the correlation of location and size to investigate the flow behavior in tracheal stenosis. This situation happens probably due to the lack of specific images of stenosis and the limitation of computer resources to reconstruct the model. Besides, there is no adequate classification scheme proposed by any researchers to suggest the regular location, size and shapes of stenosis in tracheobronchial until Freitag *et al.*, (2007) published the standard classification.

In this study, tracheal stenosis was simulated by varying the locations and sizes within the trachea region based on Freitag *et al.*, (2007). The five areas of stenosis were located between the tracheal inlet and region of bifurcation. It was expected that the presence of stenosis distal to the bifurcation would not much affect the airflow since the flow can be able to recover before entering the bifurcation region. However, as the area of the stenosis was proximal to bifurcation, the airflow passing through the stenosis was expected to change the inlet condition into the bronchus significantly.

The size of stenosis was varied into several sizes; 10% up to 80%, where the size was defined as the constriction ratio of normal tracheal lumen diameter. It was expected that small size stenosis would have no effect on the airflow pattern. However, if the location of stenosis was nearer to the bifurcation, even a little stenosis was sufficient to modify the airflow pattern. This is because the airflow would not be able to recover due to limitation of length before entering the bifurcation. Thus, it would change the inlet condition of the bifurcation region. The same situation was also expected to experience by the trachea with stenosis size more than 50% located at the top of the trachea. Although the location was far from the bifurcation, that size of stenosis was believed to be sufficient to cause the airflow exhibit nonlinear flow until the bifurcation region.

In order to explore on how significant the flow will be altered by the presence of stenosis at different sizes and locations, Computational Fluid Dynamics (CFD) had been chosen to simulate the air flow inside the trachea and main bronchi. Within the last decade, CFD had become a popular choice among the researchers. The capability of the methods is proven to give good approximation results. CFD became a useful choice in the study of airways because of its capability to investigate the complex model that is difficult to do by an experimental study. Literature shows that the human airways consist of 25 generations (branches of bronchial tree), and the diameter of each generation will reduce to less than 1 mm in the last generation, alveolar (Gemci *et al.*, 2007). Therefore, due to these complexities, CFD could give a better alternative for the studies. Recently, Romula *et al.*, (2011) suggested the use of CFD simulation method to assess the tracheal stenosis using deformable shape models.

In this study, pressure drop of airflow and velocity distribution have been shown as the result analysis. The reason to choose these two mechanical flow behaviors as a significant indicator is because theoretically, any working fluid flowing inside a constricted pipe will experience a sudden and momentous pressure drop and velocity will increase. In this case, trachea structure is almost likely same with pipe condition. Thus, any pressure drop and velocity distribution during simulation have been analyzed with a few assumptions. As the hypothesis for this study, if extreme pressure drop and great velocity increase noted during simulation, it means the condition of the real trachea with its stenosis factors are very worse and not function well to support breathing cycle. If this situation happens, it is actually the warning to the patient condition, and the medical practices should proceed with the proper treatment.

Simplified models based on Schlesinger and Lippmann, (1972) and realistic models derived from Computed Tomography (CT) scan images were used to identify the behaviour of flow parameters. Although the asymmetric simplified model was widely to simulate the airflow because it provided ideal geometry, its reliability was somewhat questionable. However, the accuracy still can be improved by refining technique of grid mesh generation and modeling of flow solver. Simplified model proposed by Schlesinger and Lippmann, (1972) was selected for this study because it provided an asymmetric geometry, fine cylinder tube without any abnormalities and totally suit to be patched with 'web-like' stenosis.

Nevertheless, the realistic geometry of airways based on CT and Magnetic Resonance Imaging (MRI) images are required in the application of practical fields such as Chronic Obstructive Pulmonary Disease (COPD) research, aerosol therapy and dose estimation, risk estimation of respiratory disease, lung cancer research and others (Yang *et al.*, 2006 and Paolo *et al.*, 2006). In this study, the images from CT scan were used together with simplified model in simulating the air flow. The images obtained were computationally converted to numerical modeling for the simulation purpose. As the CT images used in this study was noted to have abnormalities of shape at the upper third of a trachea, which is suspicions for stenosis, this study initiates a new technique of remodeling stenosis to be placed at other regular locations along the tracheal lumen. This method could be an improvement of modeling technique in patient-specific airway analysis. Limitation of images from the medical institution can be aided by regeneration or simulation of stenosis shape at different location.

The overall results show that presence of stenosis was proven to produce moderate to severe pressure drop as the locations of stenosis moved closer to the tracheal bifurcation for both actual and simplified models. Two stages of pressure drop behavior also appeared consistently as the size of stenosis increased at all sites. For all cases studied, significant changed in the velocity pattern was observed, which suggested distorted flow rates into the bifurcation.

1.2 Problem statement

Difficulties to analyze the effect of tracheal stenosis at early stage were discussed by Spittle and McCluskey, (2000), and Schuurmans M.M. *et al.*, (2004). Several researchers like Cebral and Summers, (2004), Brouns *et al.*, (2007), Jayaraju *et al.*, (2007), Arpad Farkas and Imre Balashazy, (2007) and Yang *et al.*, (2007) used an alternative method by using CFD to simulate the breathing flow condition in the trachea and main bronchi with the presence of stenosis. They had studied on how significant the factors of location and size of stenosis could affect the flow behavior in the human airway separately. Nevertheless, according to McCaffrey *et al.*, (1992) and Freitag *et al.*, (2007), the effect of location and size of stenosis come together and typically asymptomatic.

It was expected that small size stenosis would have no effect on the airflow pattern. However, if the location of stenosis was nearer to the bifurcation, even a little stenosis was sufficient to modify the airflow pattern. This is because the airflow would not be able to improve due to limitation of length before entering the bifurcation. Thus, it would change the inlet condition of the bifurcation region. The same situation was also expected to experience by the trachea with stenosis size more than 50% located at the top of the trachea. Although the location was far from the bifurcation, that size of stenosis was believed to be sufficient to cause the airflow exhibit nonlinear flow until the bifurcation region. As mentioned in introduction section, CFD was used to analyze the flow parameters inside the complex model of stenotic trachea and normal trachea. The CFD method is capable to investigate the complicated model that is difficult to do by an experimental study (Romula *et al.*, 2011).

The lack of image sources and computer processors resulted in the limitation for the numerical study of tracheal stenosis to allow the performance on the realistic model of human airway. In this study, the model derived from CT scan images was used together with simplified model in simulating the air flow. The new remodeling technique to generate the stenosis at different locations on the tracheal wall was performed to mimic the real situation.

This simulation study of tracheal stenosis is believed to be an alternative method to support the current clinical practice. The analysis of the airflow pattern can provide a possible potential risk indicator of stenosis severity to the patient.

1.3 Objectives of the research

To analyze the effects of tracheal stenosis on flow behavior of human airway, the objectives are drawn:

i. To compare the simplified and realistic model derived from CT scan images in simulating airway flow in the trachea with different flow rates.
ii. To determine the behavior of flow parameters through the trachea and main bronchi with the presence of tracheal stenosis.
iii. To investigate the correlation between location and size of the tracheal stenosis to breathing difficulties.

1.4 Scopes of the research

Towards achieving the objectives, four research scopes have been determined and listed as follows:

i. Analyze the flow pattern inside three dimensional (3D) normal trachea and trachea with stenosis under different breathing condition.
ii. The stenosis will be patched on the simplified and realistic models.
iii. Non-pulsatile breathing will be used in the simulation.
iv. Solution and discussion will be based on numerical approach only.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The chapter will review the anatomy of trachea and main bronchi, construction of simplified and realistic airway model and studies of air flow and particle depositions in human airways. Regarding the behavior of flow parameters within the airway with the presence of tracheal stenosis, this chapter will describe the description of diseases related to stenosis, classification of stenosis, the factors involved, and studies of flow in the obstructed airways will be reviewed. Besides, the correlation between the factors of location and size of tracheal stenosis and the effect of both factors in producing the significant effects to the flow behavior and causing possible breathing difficulties will be reviewed. Appendix A shows several selected publications related to this research, and present study was expected to cover most of the important parameters.

2.2 Anatomy of the trachea and main bronchi

The trachea is located anterior to the esophagus with the flat flexible tissue facing the esophagus (Figure 2.1). This flat flexible tissue enables the esophagus to expand into the tracheal space as food is swallowed. Ley *et al.*, (2002) has found that the shape of the trachea changes during the respiratory cycle from an elliptical shape during inhalation to a horseshoe shape during exhalation. Mehta and Myat (1984) observed six distinct tracheal shapes from a study of 200 patients. In order of most common, they are elliptical, C-shaped, U-shaped, D-shaped, triangular and circular. This 'windpipe' is an almost rigid organ, which can prevent collapse even under pressure, but flexible enough to allow basic motion of a human body (Satpathi *et al.,* 2003). Like the rest of the airway, it is lined by mucosa and is kept open by a series of cartilage arches. The trachea separates at the bottom into two branches (mainstream bronchi), leading to the left and right lungs. In men, the trachea is about 9-12 cm long and has a transverse anteroposterior (AP) diameter of 20 mm; in women, the tracheal length is approximately 7-11 cm, with a transverse AP diameter of 10 mm.

The mucous membrane lining the trachea is formed by ciliated pseudo stratified columnar epithelium with mucus-secreting goblet cells and small accessory tracheal glands (Figure 2.1). Connective tissue supports the epithelium and holds the glands and hence provides passage for blood vessels and nerves. In chronic inflammation, the tracheal wall may undergo remodeling and thus affect the airflow. The airway lumen may become smaller due to increased basement membrane thickness, mucosal swelling, bronchial smooth muscle and glandular hyperplasia and hypertrophy. All of these can cause tracheal stenosis.

The complexity of the airway concentrates at the bifurcation zone where the trachea divides into the left and right bronchi. The bifurcation has never been described explicitly in any of the proposed models of human airway. This is because the bifurcation zone is shaped by complex surfaces in the carina region that provides smooth transition between the trachea and the bronchi (Calay *et al.,* 2002). In addition, there is no correlation between the size of the airway and indices of carinal shape, sharpness, or variability (Hammersley and Olson, 1992). Often, the bifurcation zone is created based on the assumption that it occupies the last 20% of the trachea (Horsfield *et al.,* 1971; Hammersley and Olson, 1992). Besides that, the carinal ridge, a prominent part of the bifurcation region has great influence on the stability of the flow especially about the bifurcation region (Hammersley and Olson, 1992; Martonen *et al.,* 1994).

At the bottom of the bifurcation region, the airway is divided into two main bronchi. The geometry of right main bronchus is wider in caliber, shorter than the left, is about 2.5 cm long. The left main bronchus is smaller in diameter but longer than the right, nearly to 5 cm long. Based on the morphology of right and left main bronchus, Horsfield *et al.,* (1971) proposed the flow rates ratio imposed to the bronchi, where 55% of inlet flow rates diverge into the right bronchus while 45% of flow into the left bronchus.

In order to get a thorough understanding of the airflow, it is essential to have an accurate and realistic human lung model. However, obtaining the model that represents the realistic case of human lung airway has always been an unsolved problem. This is due to the geometry complexity of human lung, which makes the derivation of the morphologies to be precise as the realistic almost impossible. Due to the great difficulty, over the years, various models of human airway have been proposed through studies based on cadavers. They are created with alterations made on the geometry features, noticeably cartilage rings, cross-sectional shapes and carinal ridge. In all the simplified models, the protrusion of cartilage rings is absent while the random cross-sectional shapes are substituted with circular cross-sections. Furthermore, carinal ridge was made as sharp in-plane edge. These major idealizations of the human lung could lead to