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A Quick Glance at Numerical Modeling in Obstructed Human Airway

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Abstract

This quick glance focuses on the analysis of flow behavior in the obstructed human airway by the numerical approach. It is shown that the understanding of flow behavior in a patient with tracheal stenosis is imminent to the biomechanics knowledge, and the numerical study is accepted to be effective in some ways. Several current researches have initiated the new algorithm and numerical schemes, which produce significant result. This quick glance review content is divided into three sections which are based on the three research questions. The first research question is the capability of simplified and realistic model derived from CT scan images in simulating breathing flow. For the second research question, what is the behavior of flow parameters inside the trachea and main bronchi with the presence of tracheal stenosis; will review about description of tracheal stenosis disease, classification of tracheal stenosis and the factors involved, and studies of flow in the obstructed airways. The third research question, what is the correlation between the factors of location and size of tracheal stenosis to the outcomes of possible breathing difficulties

Keywords: Computational Fluid Dynamics (CFD), Tracheal stenosis and flow behaviour

1. Introduction

Difficulties to analyze the effect of tracheal stenosis at early stage were discussed by [1, 2]. Several current researches like used an alternative method by using numerical modeling, Computational Fluid Dynamic (CFD) to simulate the breathing flow condition in the trachea and main bronchi with the presence of stenosis [3-7]. 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) [8, 9], the effect of location and size of stenosis come together and typically asymptomatic.

The broad review shows the linkage between the wider body of knowledge and practical investigation to the focusing problem. This quick glance review content is divided into three sections which are based on the three research questions. The first research question is the capability of simplified and realistic model derived from CT scan images in simulating breathing flow. For the second research question, what is the behavior of flow parameters inside the trachea and main bronchi with the presence of tracheal stenosis; will review about description of tracheal stenosis disease, classification of tracheal stenosis and the factors involved, and studies of flow in the obstructed airways. The third research question, what is the correlation between the factors of location and size of tracheal stenosis to the outcomes of possible breathing difficulties; will review about the effect of both major factors in producing significant effect to the flow behavior.

2. Capability of simplified and realistic model

The trachea is located anterior to the esophagus with the flat flexible tissue facing the esophagus (Figure 1). This flat flexible tissue enables the esophagus to expand into the tracheal space as food is swallowed. The shape of the trachea changes during the respiratory cycle from an elliptical shape during inhalation to a horseshoe shape during exhalation [10]. Mehta and Myat (1984) observed six distinct tracheal shapes from a study of 200 patients [11]. 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 [12]. 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.

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 through numerical modelling 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.

Simplified models were defined by just diameters and lengths, which obviously left out the asymmetrical property, curvature, surface irregularities, transverse cross-sectional shape and spatial arrangement [13]. The airway branches were assumed to be straight hollow cylinders except in the transition region between parent and daughter airway branches [14]. Since the simplified models were created based on measurements taken from cadavers, they were subjected to tissue shrinkage and distortion during preservation [15-19]. The simplified model often lacks the airways curvature and surface irregularities, and thus results in airflow analysis different from one in real human lung [20-24].

The simplified model often lacks the realism, results in airflow different from the observed one in real human lung [24]. In order to validate the accuracy of a simplified model, the morphological irregularities of human lung should be considered [25]. Detailed mapping of the human airway can be captured with modern imaging techniques, like CT-scan and MRI [26, 27]. Without taking the airway curvature and surface irregularities, theoretical models yield flow fields significantly different from the model built based on a real CT-scan based model of airway. The CT-scan based airway model yields a more complex flow pattern [21]. Models derived from CT-scanner [20, 24] or Magnetic Resonance Imaging (MRI) exhibit the realistic anatomy of human airway [28]. Thus, the outcomes based on later models are more accurate and reliable compared to the outcomes of the theoretical models, provided same boundary conditions.

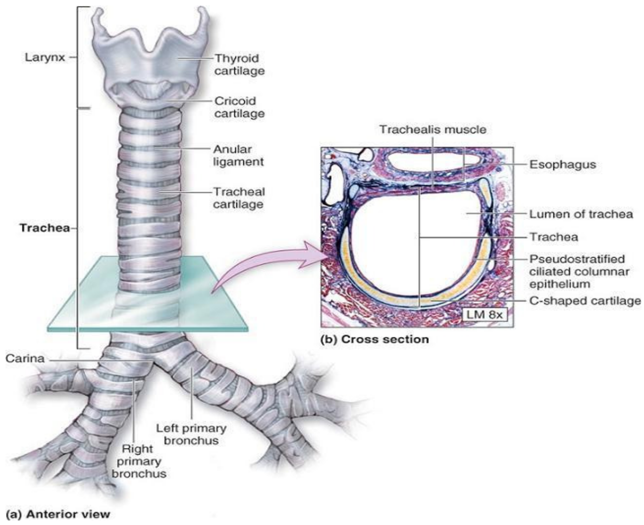

Figure 1: Architecture of tracheobronchiol. Cross section of trachea (inset)
(Kellogg Medical Community College, 2005)

3. The behavior of flow parameters inside the trachea and main bronchi with the presence of tracheal stenosis

Tracheal stenosis is an unnatural narrowing of the trachea with traumatic, neoplastic, oridiopathic causes that, despite being relatively rare, can belief threatening [29]. Increasing sizes of basement membrane thickness, mucosal swelling, bronchial smooth muscle and glandular hyperplasia and hypertrophy results the reduction of air way lumen’s diameter. Patients with tracheal stenosis often report a relatively sudden appearance of breathing impairment, which at the stage of admission to the clinic is observed when a loss of 75% or more of the air way lumen has occurred [2].

Mc Caffrey (1992) retrospectively reviewed the treatment of 72 cases of the laryngotracheal stenosis(LTS) pediatric patients [8]. He founda few potential factors that can classify the tracheal stenosis disease into different stages. These include patient’ sage, sex, etiology, site (location) of stenosis, length of stenosis and diameter of stenosis. The significant factors with regard stotracheal stenosis to the clinical symptoms are location of stenosis and diameter ofs tenosis. Freitag et al., (2007) proposed a classification system of central air way stenosis [9]. Thestenosis was classified intoa structural and ynamic type with dominant type of stenosis, degree (size) of stenosis and the location (Figure2). Their work sheet marking of location, sizes and shapes of stenosisis very beneficial to the numerical study of tracheal stenosis as they proposed a standardized classification scheme of central air way stenosis.

In human airway study, several researchers discovered the characteristics and patterns of airflow within the obstructed airways. Their findings are very beneficial to this research field.Arpad Farkas and Balashazy (2007) investigated the effect of airway's constrictions, airway's blockage, effect of sidewall and carinal tumors in the large central human airways [6]. They found that the obstructed airway caused a significant redistribution of airflow and particle deposition sites. The cross-section of tumor's bifurcation showed the changes of velocity vector field. The velocity vector concentrates towards carinal wall and had increased the airflow velocity until 10 m/s, which is equal to 60 lit/min The carinal tumor effect had proven that airflow behavior inside an abnormal structure of a trachea, and bifurcation is different and worse compared to a normal carinal.

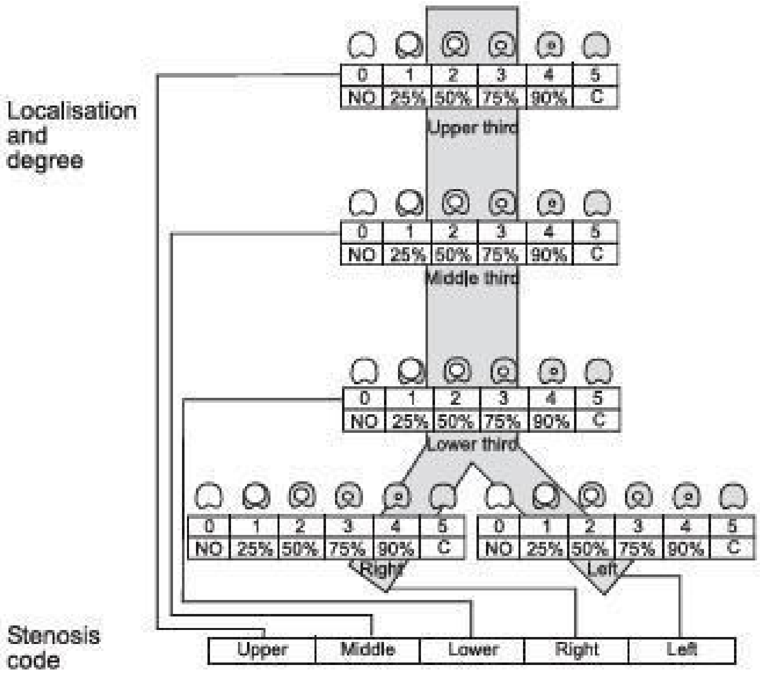

Figure 2: A worksheet marking the location, degree and type of stenosis [9].

4. The correlation between the factors of location and size of tracheal stenosis to the outcomes of possible breathing difficulties

Tracheal stenosis can influence breathing behavior, and the symptoms were not revealed until the trachea has stenosed 30% of its original size [1]. Long-segment stenosis due to congenital cause was critical, especially for infants and showed that removal of the stenosis managed to improve the breathing problem [7]. It was recommended that correct additional information is needed by medical practitioners to perform proper diagnosis [30]. Arpad Farkas and Balashazy, (2007) and Salleh et al., (2010) investigated the effect of airway's stenosis in the large central human airways and found that the obstructed airway caused a significant redistribution of airflow and particle deposition sites [6, 31].

Apart from understanding the flow, another critical factor affected by the presence of stenosis is the pressure distribution. 3D artificial stenosis has been used in one of latest study where the stenoses were patched to a healthy airway [4]. Their results showed that the overall pressure drop at rest was only affected in case of severe constriction, approximately 70% of the normal diameter (Figure 3). The results also highlighted that the pre-critical stage can be detected using computed pressure drop. The effect of increasing stenosis size was investigated and they found that the pressure drop shows modest increment with the degree of narrowing up to 75% constriction [5]. Cebral and Summers, (2004) research show decreased pressure and increased shear stress in the region of stenosis besides increment of flow velocity during inspiration [3].

Recent study by Osman K. et al., (2010) [32] was comparable with Brouns et al., (2007) [4], where they found simplified tracheal stenosis on the trachea wall begins to show a severity pattern, beginning at the size of approximately 60% of the normal diameter. When the air passes through the stenosis area, the velocity significantly increased and the pressure immediately decreased. Thus, it altered the flow due to the existence of the constricted cross-sectional area. The pattern was consistent with the Bernoulli`s Theory; the pressure reduction was accompanied by the increase of velocity. As the flow leaves the stenoses, the airway widens and the velocity will decrease to accommodate the constant flow rate. This phenomenon will directly affect the inlet flow rate to the main bronchi.

The effect of varying sizes of the tracheal stenosis to the airflow pattern had attracted several researchers. However, only few had studied the factor of location and size of stenosis, without any further investigation on the numerical study of flow behavior. A few researches proposed the regular location and sizes based on experimental diagnoses on patient [8, 9]. Both agreed that the geometry factors of stenosis, i.e. location and size were among the dominant factor in determining the outcome of the possibility of breathing difficulties.

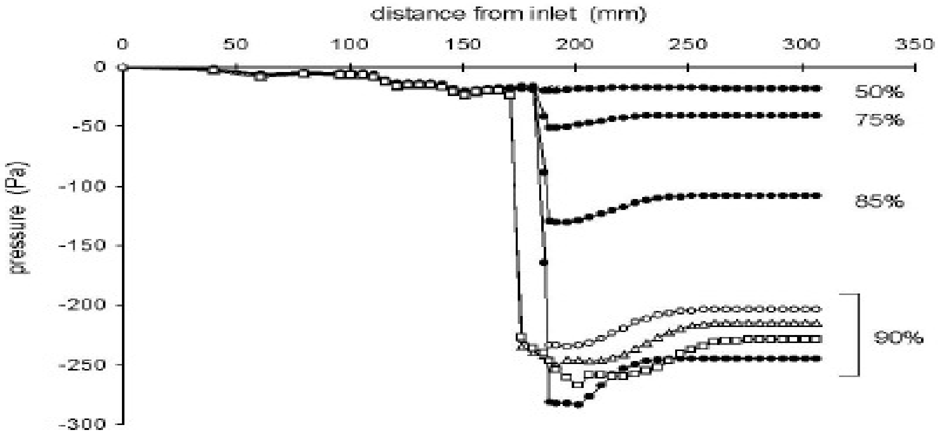

Figure 3: CFD simulated pressure with stenosis and no stenosis curves [4]

Up till now, only little study had been done among the bio-engineers and clinical professionals to see the correlation between the size and location of stenosis. Further study is needed to determine whether numerical analysis can be used as a medical scheme in diagnosis a patient with stenosis. Critical stenosis such as near the bifurcation location with any diameters is also expected to alter the flow rates into the bifurcation. The relationship between the locations, sizes of the stenosis with pressure and velocity as well as flow rate is the major contributions to this study.

5. Summary

This quick glance focuses on the analysis of flow behavior in the obstructed human airway by the numerical approach. It is shown that the understanding of flow behavior in a patient with tracheal stenosis is imminent to the biomechanics knowledge, and the numerical study is accepted to be effective in some ways. Several current researches have initiated the new algorithm and numerical schemes, which produce significant result.

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