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CFD Modelling of Aerial Mass Transfer in Tracheobronchial Airways

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Abstract: Lungs, sensitive yet most important organ that supplies oxygen to other organs to function normally. The cells of the body need energy for all their metabolic activities. The oxygen that is required to carry out their respective functions in human body is supplied by lungs. The process of taking in oxygen from atmosphere is called as inhalation and releasing out carbon di-oxide into the atmosphere is exhalation these processes together called as respiration. There is a less understanding on its function and even lesser studies with a better understanding the flow characteristics in the tracheobronchial airways a number of conditions can be studied. There are several numerical methods that can be used to develop and study a geometrical model one among those models is Computational Fluid Dynamics (CFD), it uses governing equations of fluid dynamics to study the flow characteristics.
Keywords: Lungs; Respiration; Tracheobronchial airways; Numerical analysis; Computational Fluid Dynamics (CFD).

I. INTRODUCTION

Many organs, such as the human heart, have already received a lot of attention from scientists using numerical methods. However, only few studies focused on modeling the lungs entirely, as it is probably one of the most challenging organ to simulate due to the different length scales involved, from microns for the mucociliary transport to centimeters for the airflow in the upper airways.

Respiration is one of the vital processes executed by almost all living beings. On an average, a healthy human being breaths about 10 to 15 times in a minute.

The respiration process starts from Nasal passages from where air is taken in and passing through nasal cavity it enters trachea. From trachea air enters primary bronchus then secondary bronchus followed by segmented bronchus and at the end air reaches the alveolus. Alveolus consists alveolar sacs and alveolar ducts through which oxygen enters blood capillaries and carbon dioxide is taken out from blood capillaries into alveolus [1].

The trachea or windpipe is a cartilaginous and membranous tube, extending from the lower part of the larynx, on a level with the sixth cervical vertebra, to the upper border of the fifth thoracic vertebra, where it divides into the two bronchi, one for each lung. The trachea is nearly but not quite cylindrical, being flattened posteriorly.

Obstructive lung diseases in the lower airways are a leading health concern worldwide. The lungs can have a wide range of problems that can stem from genetics, bad habits, an unhealthy diet and viruses [2]. Tracheal evaluation is a fundamental part of chest imaging. Adult tracheal anatomy is well understood, but tracheal embryology is not. There have been major advances in imaging, but radiography remains the initial imaging study for most tracheal pathology. Careful radiographic analysis can yield considerable information [3,4].

Abnormal tracheal development causes a spectrum of life-threatening anomalies. We report a newborn with tracheal agenesis and a common "esophagotrachea". Ventilation was achieved first by face mask then with an endotracheal tube. In this report, we describe the types of tracheal agenesis and discuss initial airway management [5].

There are several methods used to generate a geometric model like the model created by WEIBEL which is a simplified model assuming a symmetrical branching system [6], HORSFIELD and CUMMING generated a model based on their studies of a lung cast [7]. Stapleton et al. and Heenan et al. used idealized geometries which is based on previous studies [8,9]. Schmid et al. used high-resolution computer tomography (HRCT) to generate a geometry [10].

Computational Fluid Dynamics (CFD) is becoming a powerful tool in the medical context. It provides a good insight of physical phenomena occurring inside the human body without the need of intrusive surgical methods, which often fail to observe the desired phenomenon as they introduce perturbations [11].

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A. Governing Equations

B. The Navier-Stokes Equations

1) General Form

2) Continuity Equation

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho \vec{u}) = 0$$

3) Momentum Equation

$$\frac{\partial u}{\partial t} + (\vec{u}.\vec{\nabla})\,\vec{u} = -\frac{\nabla p}{\rho} + g + \vartheta(\nabla^2 \vec{u})$$

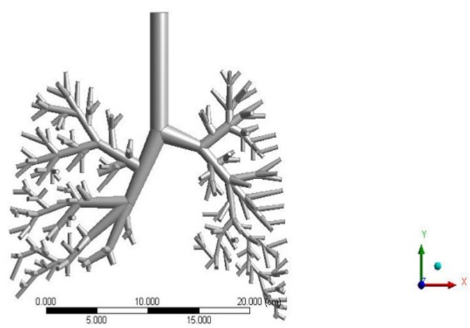
As this paper mainly deals with steady state which is time independent, the transient operator, $\frac{\partial}{\partial t}$ is neglected in both the equations.

II. PROBLEM STATEMENT & METHODOLOGY

A. Problem Statement

Flow development in airways of the lung is not understood well enough by medical science and cannot be satisfactorily measured due to the presence of a lot of bifurcations.

B. Geometry of the Problem



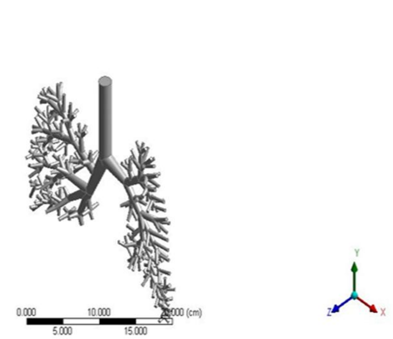


Fig.1. Geometry Fig.2. 3D view

An adult's trachea has an inner diameter of about 1.5-2 centimeters (0.6 to 0.8 in) and a length of about 10-11 centimeters (4 in.). The normal angle of the tracheal bifurcation is 70°±20 [3]. For the right and left main-stem bronchi the values were as follows: 1.16±0.17cm and 1.02±0.22 cm for men [12,13].

In this paper the tracheal diameter is taken as 1.8 cm, the diameter of right bronchus is taken as 1.16 cm and the diameter of the left bronchus is taken as 1.02 cm. These bronchi are further divided into bronchioles.

C. Meshing

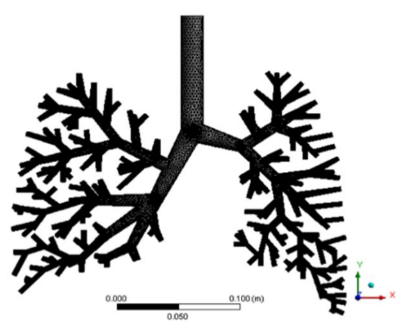


Fig.3. Mesh

Fine mesh is taken to capture the minute flow behavior for accurate results for better understanding the flow pattern.
Volume: 136.56 cubic centimeter.
No. of cells: 2064308.

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III. SOLUTION METHODOLOGY

A. Inhalation

The upper part is taken as trachea and is taken as mass flow inlet with 1.225×10^{-4}kg/s and the lower two branches are known as bronchi and are taken as pressure outlet with 0Pa of gauge pressure [14].

B. Exhalation

Bronchi are taken as velocity inlets with the values of 0.0414578m/s for right bronchus and 0.0511160m/s for left bronchus, this time trachea is taken as pressure outlet with 0 Pa of gauge pressure [14].

C. Inhalation

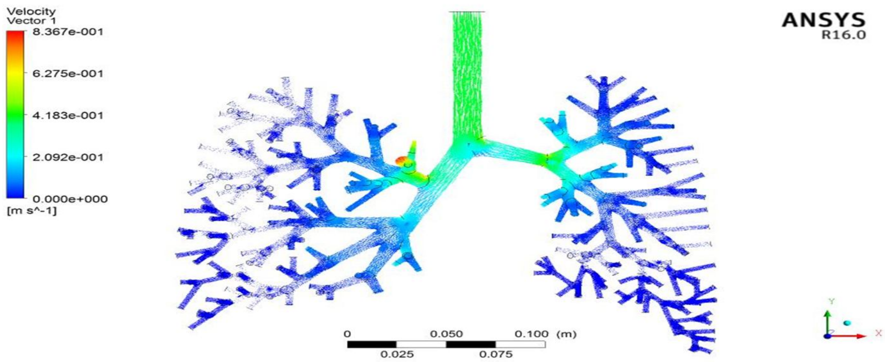

Fig.4.Velocity vector plot during inhalation.

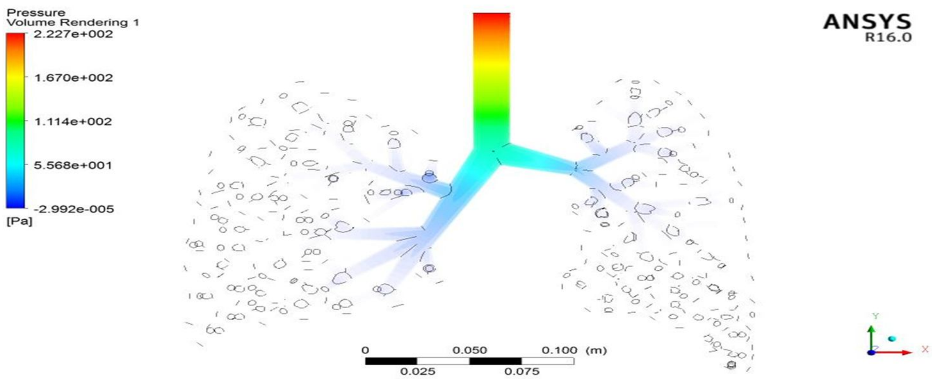

Fig.5. Volume rendering taking pressure as variable during inhalation.

D. Exhalation

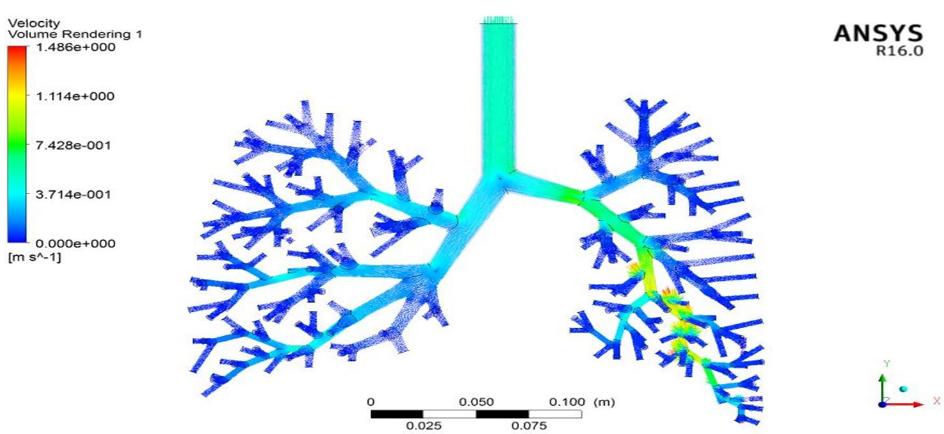

Fig.6. Velocity vector plot during exhalation.

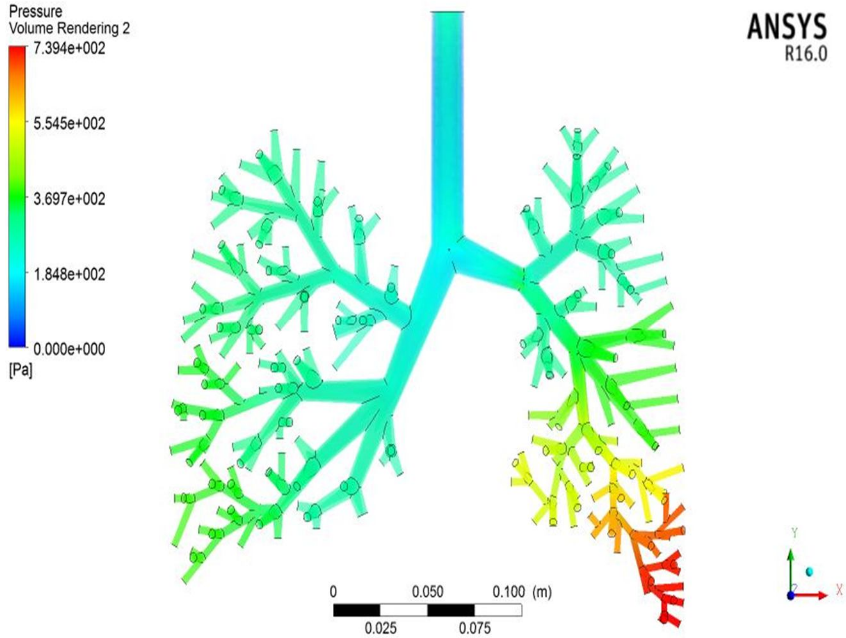

Fig.7. Volume rendering taking pressure as variable during exhalation.

IV. RESULTS & DISCUSSION

A. *Inhalation*

During inhalation the air is drawn in to lungs by means of moment of the diaphragm in the downward direction creating void, velocity vectors were taken and it can be observed that the velocity is high with the value ranging from 0.4183-0.6275m/s at the inlet i.e., trachea and gradually decreasing as the air travels towards the bronchioles which the velocity value is 0 and the lines can be seen coming out of the bronchioles, due to the branching there is a spike in the velocity reaching 0.8367m/s after entering the right bronchus and is decreased towards further branching.

Volume rendering is taken with pressure as variable and we observed that the velocity and the pressure values were within their ranges.

B. *Exhalation*

During the exhalation the diaphragm is pushed into the lungs forcing the air leaving lungs, similar to that of the process of inhalation velocity vectors were taken to study the flow behavior, these velocities at the beginning of this process is approximately 0, due to difference in velocities and the narrower left lung the velocity seems increasing with a maximum velocity of 1.488m/s and then decreases with the immediate branching and the out let velocity value ranges from 0.7428-1.114m/s.

Volume rendering is taken with pressure as variable and we observed that the velocity and the pressure values were within their ranges.

V. CONCLUSION

It can be observed that the flow is due to the expansion of the lungs creating a pressure difference which allows the air to flow into lungs from figure 4 and the flow velocity can be observed from figure 6 which is during the process of inhalation. In case of exhalation it can be observed that the lung contracts creating a pressure difference which can be seen in figure 7 resulting in the velocity which is shown in figure 6.

VI. FURTHER STUDIES

This paper deals with the flow behavior during steady state, the same boundary conditions are applied to study the flow pattern for transient state and also to be coupled with User Defined Function (UDF) to study the flow behavior at each and every time step by using time varying boundary conditions which give a complete outlook of the respiratory process.

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