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COMPARATIVE STUDY OFTHE COMPUTATIONAL FLUID DYNAMICS AND FLUID STRUCTURE INTERACTION ANALYSIS IN HUMAN AIRWAYS FLOW

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ABSTRACT

Numerous studies have been done in order to get the most accurate result that represents the flow characteristics inside the human trachea. Numerical method was the most favorite type of study chosen to simulate the model due to the complexity of the geometry and difficulties to get the real trachea to do the experimental works. In this study, one actual healthy model of human trachea was reconstructed in order to compare, the different of the velocity and pressure distribution between two types of numerical modeling analysis: Computational Fluid Dynamics (CFD) and Fluid Structure Interaction (FSI) analysis. The model was extracted using the Computed Tomography (CT) scan images to maintain the realistic geometry. Velocity, 1.24 m/s was used at the inlet and the variations of the velocity and pressure distribution along the trachea were observed. The results shown that, the implementation of the FSI technique did produce different result and flexibility of the structure wall did influence the distribution of the velocity and pressure along the trachea.

Keywords: realistic model, flow behaviour, computational fluid dynamics, fluid structure interaction.

INTRODUCTION

As we know, one of our major body systems is the respiratory system where the main component in human respiration system is the trachea. It consists of a set of cartilage rings and membranous tube where located directly below the larynx before it bifurcates into two branches: left and right bronchi then enter the lung. The flexibility of the trachea tube and the elasticity of the cartilage rings not only help the process of the breathing but also to ensure the tracheal structure is retain especially during intrapleural pressure such as sneezing, coughing etc. Despite lack of comprehensive information regarding the respiration process, the airflow characteristic in the trachea become one of the core interest from medical perspective especially when it is related to the decision making on how to treat the patients.

Former numerical studies mostly used idealized model of trachea such as Horsfield *et al.* [1] or Weibel [2] models otherwise simplified model [3]-[5]. However, these types of geometries will not include the consequence of the asymmetric pattern of the trachea structure into the airflow characteristics results [6]-[7]. The significance of using the real anatomy geometries in the studies was proven by [8] where the sudden changes in diameter inside the trachea did effect the flow separation. Sun *et al* did agree in their study that using actual images, the model accurately conserve the original configuration so the accuracy of the result is more reliable. Using the current technology, the implementation of the actual geometries of the human trachea in the numerical modelling analysis is no longer impossible. Trachea models now can be derived from the CT-Scanner [9]-[11] or Magnetic Resonance Imaging (MRI). Using this geometry, the complexity of the model can be embedded. Beside the real geometry of the trachea structure, the effect from the cartilage ring also did influence the end result of the airflow. [12]-[13] do some studies on the effect of cartilage ring in the airflow characteristics and found out that the effect of the cartilage rings increased with increased flow rate in trachea. Despite all studies have been done in order to increase the information on the properties of the flow inside human trachea, focus on the interaction between the wall structure and the flow characteristic is lacking.

The coupling between fluid flow and structural motion is playing an important role especially in biological cases. Fluid structure problems usually tricky since the structures are usually moving as well as deforming and affect the flow. It is occurs when a flexible structure interacts with a fluid. The structure will be deform, and then alter the flow pattern. Previous studies conducting the FSI analysis did manage to get additional information in their result in order to solve the structure problems [14]-[18]. In this paper, the use of Fluid Structure Interaction (FSI) technique as a benchmark for assessing the properties of flow inside the trachea was proposed. Using the images extracted from the CT scanner, the numerical analysis has been conducted and the properties of flow recorded at the end of study not only included the effect from the cartilage rings structure properties but also the trachea tube properties itself. The result will imitate the real flow closer compare to the numerical analysis without included the structure effect.

METHODOLOGY

Geometric model preparation

In this study, the actual geometry of human trachea was modelled using the CT scanner data images. Both trachea wall tube and the cartilage rings ware derived from the Digital Imaging and Communications in

Medicine (DICOM) format. From the data, there was no sign of abnormalities noted such as stenosis etc all the way the scan at the trachea wall tube, so it can be claim as a healthy human airway passage. The CT scanner images data was scanned from 60 years old Asian adult male using the axial angle where the resolution is 512 x 512 pixels and the thickness of the slice spacing is 1 mm. All the images then be extracted using MIMICS, the commercial geometry- file-conversion software.

In order to differentiate the trachea wall tube and the cartilage rings, the non- automatic segmentations of the CT scan images was done and different density were selected in order for the MIMICS software to identify each part of the trachea components. To eliminate the roughness of the curves that cause by the partial volume effects (Thomas *et al*) smothering process was done to both components, trachea wall tube and cartilage rings and the file then saved using the STL format before transferring into the solver software, ANSYS. Here, the model then undergoes the filling process to extract the fluid region inside the trachea wall tube. At the end of reconstructing the model, the components of structure region, trachea wall tube and the cartilage rings, and the fluid region will be complete. The process of reconstructing this actual model was complex and must be done in order to get the best result that achieve an estimation of both the multi-slice CT scanning and reconstruction of 3D images (Lee *et al*.).

All the components then been mesh separately, structure and fluid region, using the same software ANSYS where the model then will be analyze with and without the fluid structure interaction (FSI) affect. For result without the FSI, the structure part will be suppressed to exclude the effect. The CFD analysis will be using the ANSYS FLUENT solver while the FSI analysis will use both ANSYS FLUENT and ANSYS MECHANICAL together with ANSYS SYSTEM COUPLING.

Boundary condition

Selection of the boundary condition for both CFD and FSI analysis is very important. In CFD analysis, for the inlet, most of the studies were using the velocity as the boundary condition and zero pressure as the outflow (Malve *et al*). Same as in this study, the inlet velocity and the zero pressure were used in fluid analysis setting for both CFD and FSI analysis. The velocity of 1.24 m/s was chosen where it represents the resting activities. In order to compare the effect of the FSI, same velocity inlet value was set in the ANSYS FLUENT settings. The air, which is the material of the fluid region, was assumed to be a homogenous and Newtonian with constant viscosity and density. The flow in trachea was assumed laminar and the parameters used in this study were shown in Table-1.

Table-1. Parameter used in fluid analysis setting.

Parameters	Details
Reynolds number, *R*e	1.201×10^3 (15 l/min)
Inlet velocity, U (m/s)	1,24
Inlet pressure, P (Pa)	101325
Inlet diameter, D (m)	0.016
Density, ρ (kg/m^3)	1.176675
Viscosity, (kg/ms^{-1})	1.7894e^{-05}
Temperature, (K)	300

For structural region, the materials properties for both trachea wall tube and cartilage ring were listed below in Table-2. Both components were assumed as isotropic material where they having dissimilar stiffness due to their different role in respiration system. Cartilage ring was much more stiff compare to the trachea wall tube in order to prevent the wall collapse. In the FSI analysis, contact between the trachea wall tube and cartilage ring was assumed as bonded.

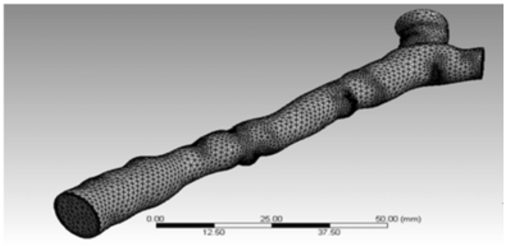
Table-2. Materials properties of the structural components.

Structural components	**Modulus Young** (MPa)	**Poison ratio**	**Density** (kg/m^3)
Cartilage rings	3.33	0.49	1140
Trachea wall tube	0.0392	0.4	1040

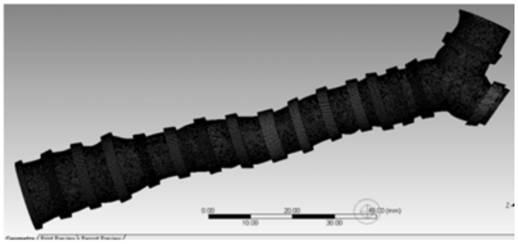
In FSI analysis, both fluid and structural region boundary condition was coupled and wall of the trachea tube was set as the intermediate between the fluid and structural region. Velocity and pressure distribution gained from the CFD analysis then been transfer to structural region before it start to calculate the effect to the wall and to the flow again.

RESULTS

All structural and the fluid region model of the actual trachea that extracted using CT scanner images that shown in Figure-1 was used in both CFD and FSI analysis. As mention before, when the CFD analysis was done, the structural were suppressed in order to eliminate the effect and the opposite when the FSI analysis was used. The analysis of the airflow inside the actual model of healthy trachea covered the distribution of the velocity and also the pressure to the fluid region to see how significant is the different between the result using with and without the FSI technique.



(a)



(b)

Figure-1(a). Fluid region after meshing (b) Structural region consist of trachea wall tube and cartilage rings after meshing

Velocity distributions

The overall velocity distribution can be seen from Figure-2 where the distributions of the velocity throughout the trachea were shown for results, CFD and FSI analysis. From the figure, the velocity distribution for CFD analysis demonstrate more uniform distribution especially at the centre line starting from the inlet until the bifurcation area. Possibility of these results is due to rigid wall that been set earlier in order to eliminate the structural effect. Although in FSI analysis, the cartilage rings play a role as a ring that support the trachea wall from collapse and been assume to make the wall rigid in some of earlier studies, still it has the elasticity factor that can make the trachea wall move and deform. Besides, the trachea wall itself is flexible structure that can deform when there are pressures present. Thus, the distribution of the velocity inside the trachea is no longer uniform as shown in Figure-2(a) and Figure-2 (b).

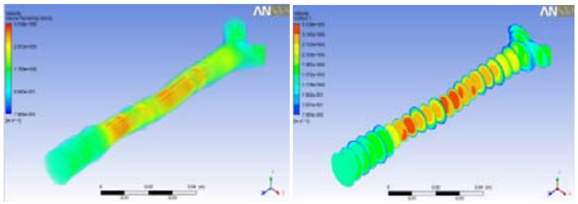


Figure-2 (a). Velocity distributions inside the healthy trachea using FSI method in volume and plane contour view.

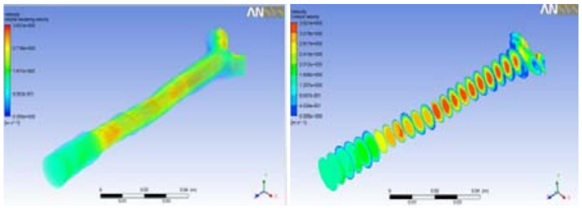


Figure-2 (b). Velocity distributions inside the healthy trachea using CFD method in volume and plane contour view.

Velocity distributions then were plotted along the centreline of the main bronchi and also at the centreline of both left and right bronchus to give a full picture of the effect between the techniques: Figure-3 and Figure-4 show the velocity distribution at the centre line and from both figures, the changed of the velocity between the inlet and bifurcation area were calculated and show a different value. It is prove that the FSI analysis did effect not only the velocity distribution but also the velocity speed.

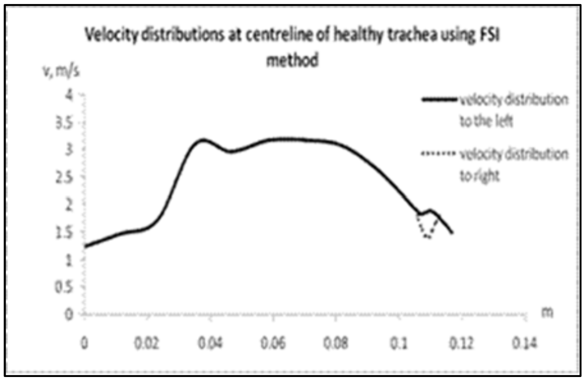


Figure-3. Velocity distributions at centreline of healthy trachea using FSI method.

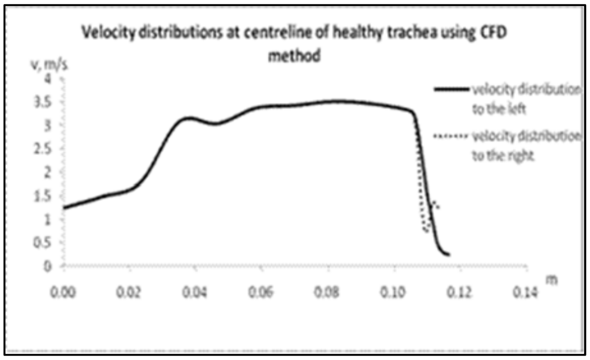


Figure-4. Velocity distributions at centreline of healthy trachea using CFD method.

Pressure distributions

Beside the velocity, pressure distribution also plays an important role in deciding the patient condition and treatment. Therefore, in this study, these results are included. As expected, generally, the pressures were distributed equally for CFD analysis and not for FSI analysis. The pressure distribution and pressure drop between the inlet and bifurcation area for both cases can be seen in Figure-5(a) and (b) and clearly shown in graphs, Figures 6 and 7. From Figure-5 (a) and (b), it can be summarize that the pressures distributions at both outflow branches especially at the centreline are same and uniform if the analysis only limited to CFD technique but it is different when the structural effect was included. The pressure mapping change due to the movement and deformation of the structural. At the same time, the pressure distribute unequally.

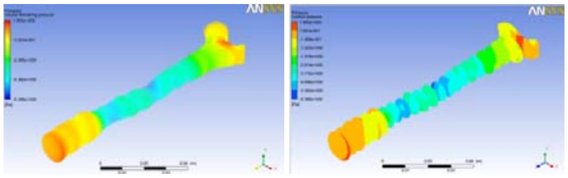


Figure-5 (a). Pressure distributions inside the healthy trachea using FSI method in volume and plane contour view.

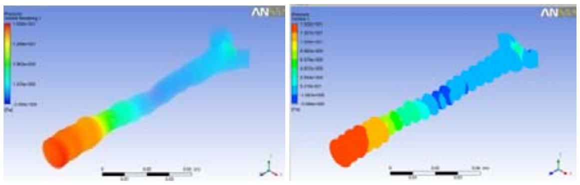


Figure-5 (b). Pressure distributions inside the healthy trachea using CFD method in volume and plane contour view.

The graph shown in Figure-6 and Figure-7 were plotted at the centreline of the trachea and the different is significantly shown between the CFD and FSI analysis. The structural effect did influence greatly to the pressure mapping although the velocity inlet given were small. It can be summarize that, if the inlet velocity increase, the effect will be greater. In term of pressure drop between the inlet and the bifurcation area, both cases show a small changes and it is because the flow rate induced at the beginning of the trachea was assumed as sleep activities where there is no large movement or bigger behavior were done.

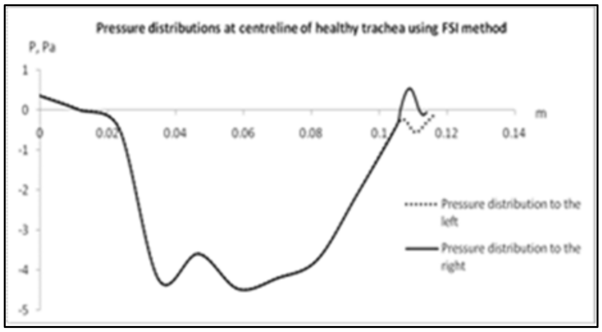


Figure-6. Pressure distributions at centreline of healthy trachea using FSI method.

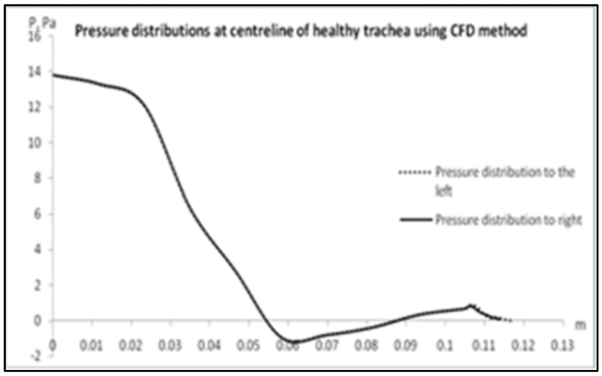


Figure-7. Pressure distributions at centreline of healthy trachea using CFD method.

CONCLUSIONS

In conclusion, the CFD analysis can be used to simulating airflow in human airways but the objectives of the study should not be related to structural effect as the results can be neglected. However, the FSI analysis provide more accurate results because it mimicking the real situation of the situation while breathing. This technique was very suitable to implement in biomechanics studies such as human respiratory.

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