Study of Inlet Velocity in the flow of Air in an Obstructed airway from Chronic Bronchitis

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Objective

The objective of this study is to observe the effect of inflamed bronchioles, due to COPD. We compare velocity profiles of a healthy tracheobronchial model to an obstructed model.

Introduction

Bronchitis is a respiratory disease in which the mucus membrane becomes inflamed. It is caused by a respiratory infection often brought on by the common cold or influenza. Bronchitis can be categorized as either an acute or chronic case.

Acute bronchitis lasts for about three weeks and is characterized by severe coughing. The coughing is due to large amounts of mucus build up within the lungs. Treatment is often directed at the symptoms of the bronchitis and not the cause, such as treating a sore throat or fever. This is because if treated with antibiotics, bacteria may become drug resistant and may lead to a worsening of the condition or mortality of a patient. Because most cases are viral, acute bronchitis will eventually clear up without much treatment.
Chronic Bronchitis or COPD is characterized by a long term cough, which is estimated to last three months to a year. Similar to acute bronchitis, chronic bronchitis causes the inflammation of the bronchioles which hinders airflow to and from the lung. One of the main causes for chronic bronchitis is smoking, followed by inhalation of pollutant known to cause irritation to the respiratory tract. The treatments for Chronic Bronchitis include bronchodilators, which will reduce the inflammation of the inner wall of the trachea. Other treatments include steroids to chemically react with the inflammation to reduce the inflammation.

Theory

The flow of air through the trachea to the bronchioles is assumed to be fully developed laminar flow. The velocity field, along any point in the respiratory tract, is solved by using Navier-Stokes equation (NS) (1), together with the continuity equation (2).

\[ \rho \left( \frac{\partial V}{\partial t} + V \cdot \nabla V \right) = -\nabla P + \nabla^2 V \quad (1) \]

\[ \nabla \cdot (V) = 0 \quad (2) \]

Where: \( \rho \): Density  \quad P: Pressure  \quad t: time  
\( V \): Velocity  \quad \nabla: del operator
The moving air is also assumed to be incompressible, having a constant density in time and space, inside the control volume all throughout the flow field. Furthermore, the conservation of mass is assumed; implying the mass of air coming into the trachea is the equal to the mass of air leaving the respiratory tract through the bronchioles. Another assumption taken into consideration is that the fluid is at steady state, non-time dependent and is a Newtonian fluid. No slip boundary condition is imposed on the walls.

**Model:**

Our 3D model was made referencing “Anatomically based three-dimensional model of airways to simulate flow and particle transport using computational fluid dynamics”\(^1\). This study modeled particle deposition from the trachea to the bifurcated bronchi to ultimately compare their results to aerosol delivery of medication within the lungs. The model from this paper is a three dimensional model with 17 bifurcations and 7 generations of bifurcations. Each generation of bronchi becomes smaller in diameter.

We initially created our 3D model on SolidWorks, but we were unable to convert it to COMSOL. Our COMSOL model’s bifurcations are not completely smoothed. The newly modeled bifurcation points downwards. The simplified model is still representative of the basic
structures found within the lungs: a trachea to bronchial bifurcation and multiple generations of bifurcations.

The purpose of our model was to simulate airflow through a bronchial tree and show the most realistic values of fluid flow passing through a bifurcation. Computational analysis of airflow through bronchial trees is very common; however, most other studies have studied symmetric bifurcation within the bronchioles. This model is asymmetric at almost every bifurcation. COMSOL Multiphysics was used to create and compute a total of 3 generations of bifurcating bronchioles with 8 different bifurcations and trifurcations. Our study was only concerned with laminar flow, so curvature of the angles of certain bronchioles was not included. The curves may cause turbulent flow and that is not in the interest of this study.

The inlet velocity we used was a normal velocity of 1.5 m/s, not a parabolic flow, in the downward direction through the trachea. On the opposite side of the model, we included several outlets. To ensure we have an accurate model, we had to consider about how air flows through the trachea and bronchioles. When a person inhales, their lungs expand and create a negative pressure, which will cause a sucking of air through the only inlet, the trachea. To model this, we set the outlet pressures to -101,325 Pa so that we can replicate the negative pressure created by the lungs.

Initially these outlets were set at standard atmospheric pressure and as we were analyzing the pressure throughout the model, we noticed an increase in pressure at one of the final generations in the bronchioles. This is counter intuitive, because we know that fluid flows from higher pressure to lower pressure.
Geometry

The parent trachea had a radius of 1.25 cm and a length of 11 cm. Tracheal dimensions were not specific to a certain person, but a generalization due to varying tracheal sizes among people. Bifurcations were created by using short cylinders, rather than cones, to determine direction and remove convergence. Daughter branches in the first bifurcation were separated by a total of 70° and were conical in shape. Cones began with a top radius of 1.25 and a bottom radius of 1.00. The conical shape made building more generations of bifurcations much simpler because the parent was cylindrical. Generations were constructed by opening separate windows of COMSOL and differentiating parent and daughter sizes. We were able to import the differentiated bifurcations onto with the parent cylinder on conical daughter branches by using trigonometric analysis and formed a union between the two geometries. As a final product we obtained various outlet sizes that represent smaller bronchial branches and various amounts of alveoli.

<table>
<thead>
<tr>
<th>$R_1$</th>
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<tbody>
<tr>
<td>$R_2$</td>
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<tr>
<td>$R_3$</td>
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<td>$\Theta_1$</td>
<td>70°</td>
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<td>$\Theta_2$</td>
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<tr>
<td>$\Theta_3$</td>
<td>70°</td>
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<tr>
<td>$\Theta_4$</td>
<td>30°</td>
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</table>
Mesh dependency did not seem to be a huge concern in our model. We constructed it initially with an extremely course mesh to make sure COMSOL would run our model without errors. A comparison of mesh sizes that were finer than our setting showed that many of the values and profiles were very similar. The final product ran with the “coarser” physics controlled mesh.

Results and Analysis
Initially, a 2D model of the trachea and bronchioles was created. The velocity profile of air through the trachea was calculated using COMSOL Multiphysics. Air flowing through the trachea to the bronchioles is considered to be Newtonian and incompressible. The walls of the trachea and bronchioles are solid boundaries without any flux and a no slip condition at a steady state. In our model we designed it to have an obstruction on both sides of the bronchioles extending from the trachea.

The study, “The effect of inlet velocity profile on the Bifurcation COPD airway flow”\textsuperscript{2}, evaluated velocity profiles throughout the simple 3D bronchial tree with different inlet velocity skews. Their results showed that the velocity profiles were skewed at the lower area near the bifurcation\textsuperscript{1}. The models that they created to make their studies were 2D, simple, and symmetric, unlike a realistic system where a bronchial tree is asymmetric and complex. They used a constant Reynolds number, which we did not take into account into our model.
Important conclusions to take from this study are that inlet velocities affect velocity fields greatly and that uniform inlet velocity will cause a large pressure drop after several generations.

Figure 8 shows a cut line taken from the trachea. It illustrates a uniform velocity profile. This profile expresses that our model is similar to that of the literature data. Uniform data is expected because there is nothing affecting air flow. If inlet velocity is uniform, the cut line should also be expected to be a uniform velocity profile.
Figure 10 shows a cut line on the right bronchiole and Figure 11 displays a negative skewed velocity profile. A negative skewed profile, in this case, shows that the velocity closest to the bifurcation is the highest in magnitude which is consistent with literature data.

Figure 12 shows a cut line on an inflamed bronchiole. The velocity profile that was obtained was positive-skewed. This profile tells us that the velocity in the obstructive bronchiole will exert a higher velocity after the bifurcation. This profile is consistent with the literature data.
In summary, our model and their velocity profiles demonstrates a proper air flow through a replicated respiratory system. The velocity fields in our model can be compared to the literature model as well be confirmed that the velocity profiles are accurate to what we wanted to express.

Two specific studies were taken into consideration to compare the healthy and inflamed bronchioles: zero outlet pressure and negative outlet pressure. Zero outlet pressure implies that air flow through the model is only affected by the inlet velocity starting at the entrance of the trachea. Negative outlet pressure is defined by placing a negative pressure to draw air flow downward while modeling. We make this distinction because some papers studied vary outlet pressures.²

**Zero Outlet Pressure, No Obstruction**

Figure 14 is a full velocity profile of our model with zero outlet pressure. The maximum velocity is concentrated in the trachea and dissipates after the first bifurcation. The velocity flow is evenly divided between the two bronchi after the first bifurcation because air is being directed only by the bifurcation and not by any
form of outlet pressure.

A cut plane taken 6 centimeters down the trachea shows the effects zero outlet pressure has on velocity profile. The arrows on Figure 15 represent the magnitude of the velocity field. It is noted that the flow pattern is directed toward the center of the trachea, away from the walls. This is a uniform velocity profile which is reflective of the results in the 2D model, which also utilized zero outlet pressure.

The color map in Figure 15 also reflects a uniform velocity profile; velocity increases from lower to high moving toward the center of trachea. It is important to note that the velocity profile is not parabolic because it remains evenly uniform with no large velocity spikes in the middle of the slice.

A second cut plane is taken two generations from the first bifurcation (in the left bronchi) to observe its velocity flow field.

The color map in Figure 16 is that of a skew velocity profile, much like the profiles found in the 2D
model. A skew profile is expected because of the effects that bifurcations and zero outlet pressure have on velocity. The bifurcation directs airflow between daughter generations so after two generations of bifurcations, the maximum velocity pictured is much less than that of the trachea. Also, bifurcations disrupt the initially uniform velocity profile, which is also explains the skew profile. The velocity arrows’ magnitude also represents a skew profile, with higher magnitude located on the top of the profile and smaller closer to the bottom.

Zero outlet pressure produces skew velocity profiles in daughter generation bronchioles because the velocity profile is affected solely by the bifurcations it passes through and not by a change in pressure drop. No obstruction is introduced because it would not produce realistic or useable data.

**Negative Outlet Pressure, No Obstruction**

To create a more accurate model, negative outlet pressure was added to represent the negative pressure created in the lungs during inhalation. A study modeling airways in 3D applied a negative outlet pressure to their model\(^2\). The outlet pressure from this study varied based on the diameter of each individual bronchiole.

For our model, we assumed a pressure of -101,325 Pa was applied at each of the outlet bronchioles in order to draw airflow downward.
Figure 17 is the overall velocity profile of the model. A slice is taken on the Y-Z plane to show the total velocity through the model, not just surface velocity. Velocity is notably non-uniform in the daughter generations after the first bifurcation. The right bronchial after the bifurcation has higher velocity concentration than the left bronchiole.

The cut plane in Figure 18 is taken 6 cm down from the top of the trachea. The color map shows a parabolic velocity profile which is consistent with what is to be expected. In comparison to the zero outlet pressure model, the diameter of the concentrated maximum velocity is much smaller due to the negative outlet pressure acting as a downward force. Velocity is greater in the center because airflow is being pulled downward.

Negative outlet pressure and the asymmetric geometry of the model are responsible for a non-uniform velocity field in the trachea. Air flow is drawn downward by differing sums of negative pressure which explains the swirling pattern in the velocity field. The arrows in the center of the cut plane that are directed towards the top left are representative of air flow directed over the bifurcation.
The cut plane Figure 19 is taken two generations after the first bifurcation (in the left bronchi). The color map in Figure 19 shows parabolic velocity profile which is consistent with literature data of a cut plane after bifurcation in a 2 dimensional model\(^1\). Because this slice is taken closer to the outlet, the velocity field is much more unidirectional than in the trachea. The direction of the arrows is representative of expansion in an outward direction that would occur in the lungs during inflation.

**Negative Outlet Pressure, Obstructed Bronchiole**

An obstruction is added to represent inflammation within the bronchioles. The obstruction is located in the second generation of bronchioles of the left bronchi. There is a notable ellipse shape section missing from the bronchiole.

A slice is taken two generations after the first bifurcation (in the left bronchi) to compare the velocity profiles of an inflamed bronchiole to a healthy bronchiole.
The color map shows a skewed velocity profile present in the bronchiole. The obstruction concentrates airflow in a non-uniform profile which is shown in dark red in the image. This profile is in agreement to the data from the 2D model study.

The highest magnitude arrows are concentrated around the maximum velocity on the color map which confirms also confirms a skewed velocity profile. They are directed toward the outward wall, much like in the non-obstructed model, showing that the lungs would still expand, even with a large obstruction.

**Conclusion:**

This study displayed the effect of inflamed bronchioles due to Chronic Obstructive Pulmonary Disorder (COPD). We compared the velocity profiles in our model to literary values of other 3D models using computational fluid dynamics. Once we confirmed the accuracy of our model, we compared the velocity profiles of a healthy bronchiole with positive and negative outlet pressure. Negative outlet pressure was applied because the act of inhalation requires a negative pressure in the lungs to create an inlet velocity. We wanted to simulate the most accurate model of the upper respiratory system. With further studies, this can be applied to application of aerosol drug delivery for patients with chronic obstructive pulmonary disorder.
Appendix

Since we began, we have been working to develop a realistic model that resembles the actual trachea characterized by various bifurcations extending into branches of the bronchioles. This section includes the models that have been built to run in COMSOL Multiphysics. However, they are not used to compare to any literature data to, due to the high probability of running into an error.

Particle Tracing Module

This module is another functionality of COMSOL Multiphysics. It allows an accurate prediction of the trajectory of a particle as it is released from the inlet position and it’s interaction with a boundary in a fluid. For our model, we simulated the particle flow path towards the bronchioles on a 3D model, having 2 generations. It is a transient model, having time-dependency.

The particles are released from the upper portion of the trachea. The boundary conditions imposed on the walls of the trachea and bronchioles are notated as “bounce”, which implies the particles will bounce back up on colliding with the wall. Computing the model on COMSOL Multiphysics, took 1 day, 17 hours, 38 minutes, 28 seconds.
The results couldn’t be analyzed because of lack of understanding of time dependent model and long period of time required to compute a model.
Works Cited
