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## ENERGY DISSIPATION IN AN ASYMMETRIC TRACHEOBRONCHIAL TREE: A CFD ANALYSIS

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### ABSTRACT

The aim of this work is to study the airflow resistance in an asymmetrical tracheobronchial tree model. Computational Fluid Dynamics (CFD) simulations were made and the results have been analysed and compared to literature. New correlations relating the viscous flow resistance to local Reynolds number and airway geometry are proposed. Further work includes the implementation of these correlations in a mathematical lumped model to analyse the influence of the inertial effects and lung asymmetry on the ventilation distribution in the lungs.

**Keywords:** airflow resistance, tracheobronchial tree, CFD, lumped model

### INTRODUCTION

The lungs are a complex organ of which the primary function is the exchange of oxygen and carbon dioxide with the environment. For a healthy individual, breathing is a natural process that takes place fluently. However, several lung diseases such as asthma or chronic obstructive pulmonary disease cause breathing to be extremely difficult and uncomfortable. The field of lung mechanics is an important research topic to better understand the breathing process. In particular, the pulmonary airway resistance is a main clinical indicator. This resistance is the result of the airway resistance and the tissue resistance [1]. The airway resistance is defined as the pressure difference between the alveoli and the mouth divided by the volumetric flow rate into the lungs. It is strongly linked to the inertial effects and the undeveloped character of the velocity profile of the flow in the airways [1]. It is generally

accepted that the airways up to the seventh - tenth generation of the tracheobronchial tree contribute to the most part to the airway resistance in the normal adult human lungs [2]. Different studies attempted to characterise the airway resistance in a healthy human adult. Pedley et al. [3] introduced the definition of the parameter  $Z$  as the ratio of the actual energy dissipation in an airway,  $\Delta E$ , to the Poiseuille dissipation,  $\Delta E_P$  (i.e., the energy dissipation if a Poiseuille flow were fully developed within the airway). They proposed a correlation for  $Z$  based on measured inspiratory flow profiles.

$$Z = \frac{\Delta E}{\Delta E_P} \quad (1)$$

However, their approach relies on two important assumptions. First, they use the anatomical model of Weibel et al. [4], which is based on the assumption that the lungs can be represented as a symmetrical, dichotomous branching system [5]. It is known that the lungs present a natural asymmetry where each parent airway gives rise to one smaller and one larger daughter airway [6]. Secondly, the authors neglect the viscous pressure drop in the bifurcation region [7]. These two assumptions result in an overestimation of  $\Delta E$ , as already evidenced by other researchers [7] [8].

Several studies aimed to analyze the airflow and velocity profiles within a physiological asymmetric lung geometry. Yet, to our knowledge, for an asymmetric lung geometry, no revised correlations for  $Z$  have been proposed to date. Additionally, the asymmetric lung geometries used are often based on Computed Tomography (CT) scan of one adult, causing the results to be subject-specific. Therefore, in this work, the asymmetry of the lungs is introduced by the use of a systematic branching asymmetry as proposed by Florens et al. [6]. The objective of this work is to propose extended correlations of  $Z$  using a model approach and taking into account the complex nature

of the lungs, in particular its geometry. More specifically, the objective is to propose correlations taking into account four parameters: the degree of asymmetry of the lungs, the nature of the airway (small or large airway), the local Reynolds number within the airway,  $Re$ , and the ratio of the length to the diameter of the airway.

## PROBLEM STATEMENT

### Geometry of the system

Computational Fluid Dynamics (CFD) simulations of airflow during inspiration and at rest were performed on a tracheobronchial tree composed of three consecutive generations. The airways are referred to with a couple  $(i, j)$ , where  $i$  is the generation number and  $j$  is the airway number within this generation ( $j = 1, \dots, 2^{i-1}$ ). A general representation of this tree is shown in Figure 1.

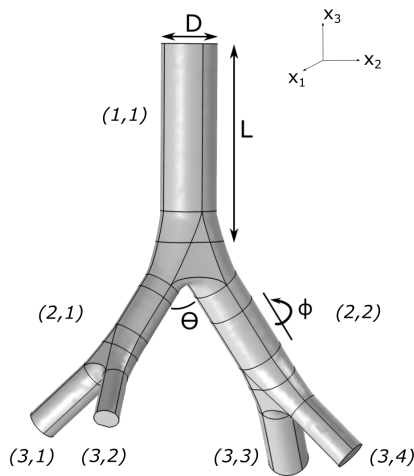


Figure 1: Representation of the tracheobronchial tree geometry composed of three generations. Each airway is referenced with coordinates  $(i, j)$ .

The tree geometry is parameterized according to four different parameters. The first parameter is the branching asymmetry,  $\delta$ , which is characterized by two different scaling ratios,  $h_{\min}$  and  $h_{\max}$ .  $h_{\min}$  and  $h_{\max}$  are linearly related to  $\delta$  and are the ratio of the diameter of each smaller and each larger daughter airway to the parent diameter, respectively. In the case of a purely symmetrical tree ( $\delta = 0$ ),  $h_{\min} = h_{\max} = h_0 = 2^{-1/3}$ . This is in accordance with Weibel's "A" model [4].  $\delta = 1$  corresponds to physiological values for  $h_{\min}$  and  $h_{\max}$ , derived by Florens et al. [6]. The second parameter is  $\alpha$ , defined as the ratio between the length,  $L_{i,j}$ , and diameter,  $D_{i,j}$ , of an airway with coordinates  $(i, j)$ .  $\alpha$  is independent of the coordinates  $(i, j)$ .

In this work, three different values are considered for  $\delta$  (0, 0.5 and 1) and  $\alpha$  (2.5, 3 and 3.5). The third and fourth parameters are the branching angle,  $\theta$ , and the azimuthal angle,  $\phi$ , the latter being angle of rotation between consecutive bifurcations (see Figure 1).  $\theta$  is set to  $70^\circ$  and  $\phi$  is equal to  $90^\circ$  [8].

## Modeling assumptions and equations

For the considered CFD simulations, two major assumptions are made. First, an incompressible Newtonian fluid is considered. Secondly, isothermal conditions are assumed. Under these assumptions, the airflow within the tracheobronchial tree is analyzed by solving the continuity and Navier-Stokes equations, in a stationary state and in a dimensionless form:

$$\frac{\partial u_k}{\partial x_k} = 0 \quad (2)$$

$$Re_{1,1} u_l \frac{\partial u_k}{\partial x_l} = - \frac{\partial p}{\partial x_k} + \frac{\partial^2 u_k}{\partial x_l \partial x_l} \quad (3)$$

where  $(x_1, x_2, x_3)$  are dimensionless cartesian coordinates.  $u_k$  is the  $x_k$ -component of the dimensionless air velocity and  $p$  is the dimensionless pressure.  $x_k$  is scaled by the diameter of the first generation,  $D_{1,1}$ ,  $u_k$  is scaled by the average velocity at the inlet of the first generation,  $U$ , and  $p$  is scaled by the ratio  $\frac{U\mu}{D_{1,1}}$ .  $Re_{1,1}$  is the Reynolds number in the first generation of the tracheobronchial tree, defined as  $\frac{UD_{1,1}\rho}{\mu}$ , where  $\rho$  is the density of the air and  $\mu$  its dynamic viscosity.

### Boundary conditions

The boundary conditions for the airflow are:

- A constant dimensionless velocity at the inlet of the tracheobronchial tree equal to 1.
- Zero pressure at the four outlets ( $p = 0$ ). Using a mathematical lumped model on the air flow in a complete lung (not presented here), plausible pressure distributions within the tracheobronchial tree were obtained. These distributions have been used to verify that setting the outlet pressures to zero or setting appropriate pressure distributions has no significant influence on the Z-values.
- No-slip conditions at the solid surfaces.

## NUMERICAL PROCEDURE

### Solver and meshing

The equations and boundary conditions defining the problem are solved using COMSOL Multiphysics® 5.3. It is based on the Finite Element Method (FEM). First-order discretization schemes are selected for the pressure and the velocity. The discrete equations are solved with the default solver using the algebraic multigrid method resulting in good convergence characteristics. The mesh is constructed using default physics-controlled meshing sequences. Independence of the simulations results on the mesh size has been verified.

### Post-processing

For each geometry,  $Re_{1,1}$  varies from 10 to 1000. These values correspond to inspiratory flow conditions in genera-

tions one to ten for a healthy human adult at rest. The post-processing of the simulations consists in evaluating  $Z$  in each of the four airways of the third generation of the bronchial tree by using the following equation

$$Z = \frac{\Delta \tilde{E}}{\Delta \tilde{E}_P} \quad (4)$$

with  $\Delta \tilde{E}$  the actual dimensionless energy loss and  $\Delta \tilde{E}_P$  the dimensionless energy drop if the flow within the airway were a fully developed Poiseuille flow. The methodology to calculate  $\Delta \tilde{E}$  and  $\Delta \tilde{E}_P$  is based on the approach of Wells et al. [8], adapted to include the case of asymmetric lung geometries. Note that equation (4) is equivalent to evaluating the ratio of the true flow resistance,  $R$ , to the flow resistance if the flow within the airway were a fully developed Poiseuille flow,  $R_P$ .

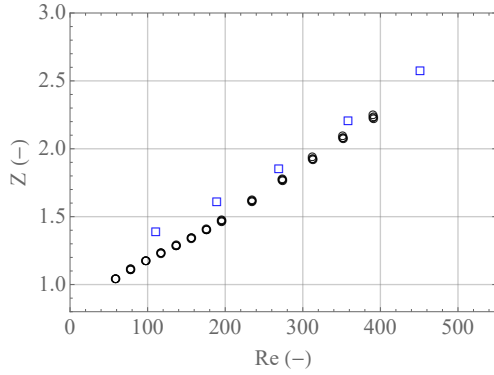


Figure 2:  $Z$  in the airways of the third generation of bronchial tree vs the local Reynolds number within these airways. The geometry is defined by  $\delta = 0$  and  $\alpha = 3.5$ . ( $\square$ ) are the numerical results of Wells et al. [8]. ( $\circ$ ) are the numerical results of this work.

### Comparison with literature

To assess the validity of our numerical procedure, the results for a geometry defined by  $\delta = 0$  and  $\alpha = 3.5$  are benchmarked against those of Wells et al. [8], as shown in Figure 2. This shows that our approach correctly evaluates the energy loss within an airway of the bronchial tree. The small difference between our results and those of Wells et al.[8] is most likely due to the different methodologies used for creating the geometry of the airway bifurcations.

### RESULTS AND DISCUSSION

The results of the CFD simulations for the four airways of the third generation in asymmetric lung geometries ( $\delta = 0.5$  and  $\delta = 1$ ) are shown in Figure 3. Interestingly, the results show little dependency of  $Z$  on the nature of the parent (i.e., small or large parent). It can be observed that, for a fixed nature of the airway within its own generation (small or large),  $Z$  takes a value that is larger than one when  $Re \approx \alpha/0.06$ . Here, a parallel can be drawn with the well-know correlation

$L_e/D = 0.06Re$ , relating the entrance length number,  $L_e$ , (i.e., the length needed in a tube or duct to establish a fully developed Poiseuille flow) with  $Re$  and the diameter of the tube or duct,  $D$ , for a laminar flow.

A clear distinction can be made between the two smaller ( $Z_{small}$ ) and the two larger ( $Z_{large}$ ) airways within the third generation. For a fixed asymmetry and at equal values of  $Re$ ,  $Z$  is larger in the two larger airways than in the two smaller airways. For the large airways, three important observations can be made. First, a linear relation between  $Z_{large}$  and  $Re$  is observed. Secondly, at a fixed value of  $Re$ ,  $Z_{large}$  increases as the asymmetry,  $\delta$ , of the airway increases. Lastly, it can be noticed that, for a fixed value of  $Re$ ,  $Z$  decreases as  $\alpha$  increases. This is expected as a larger value of  $\alpha$  corresponds to a longer distance for the velocity profile to develop towards a Poiseuille flow. Regarding the smaller daughter airways, at a fixed value of  $Re$ ,  $Z_{small}$  decreases as the asymmetry,  $\delta$ , increases. The relation between  $Z_{small}$  and  $Re$  or  $\alpha$  appears to be more complex than for the larger airways. These phenomena require further investigation. Nevertheless, using the 'NonlinearModelFit' function implemented in the software Mathematica®, the following correlations are obtained for  $Z$  for the large airways as well as for the small airways:

$$Z_{large} = 1 + (c_1 - c_2 \alpha)(1 + c_3 \delta)(Re - \frac{\alpha}{0.06}) \quad (5)$$

$$Z_{small} = 1 + c_4(1 - c_5 \delta)(Re - \frac{3}{0.06}) \quad (6)$$

with  $c_1 = 41.7 \times 10^{-4}$ ,  $c_2 = 1.25 \times 10^{-4}$ ,  $c_3 = 0.103$ ,  $c_4 = 37.7 \times 10^{-4}$  and  $c_5 = 0.653$ . As opposed to the correlation for  $Z_{large}$ , the correlation of  $Z_{small}$  is not sensible to a variation of  $\alpha$ , but is based on a fixed value of  $\alpha$  equal to 3.

In a further stage of this study, equations (5) and (6) are to be implemented in a mathematical lumped model of the lungs in order to study the influence of the inertial effects and of the heterogeneous geometry on the overall resistance of the lungs and on the distribution of ventilation.

### CONCLUSIONS

The influence of the geometry of the tracheobronchial tree on the energy dissipation in an airway has been investigated. This dissipated energy appears to be little influenced by the nature of its parent airway (i.e., small or large parent). Including the heterogeneity of the lung geometry allows making a distinction between the behaviour of the small and the large airways within an airway generation. The large airways show a linear dependency on its local Reynolds number. Also, a clear relation between the geometrical ratio of the length to the diameter of the airway can be seen in case of the large airways. The behaviour of the small airways appears to be more complex and requires further investigation. Nevertheless, a correlation on the energy dissipation could be proposed for both airway types.

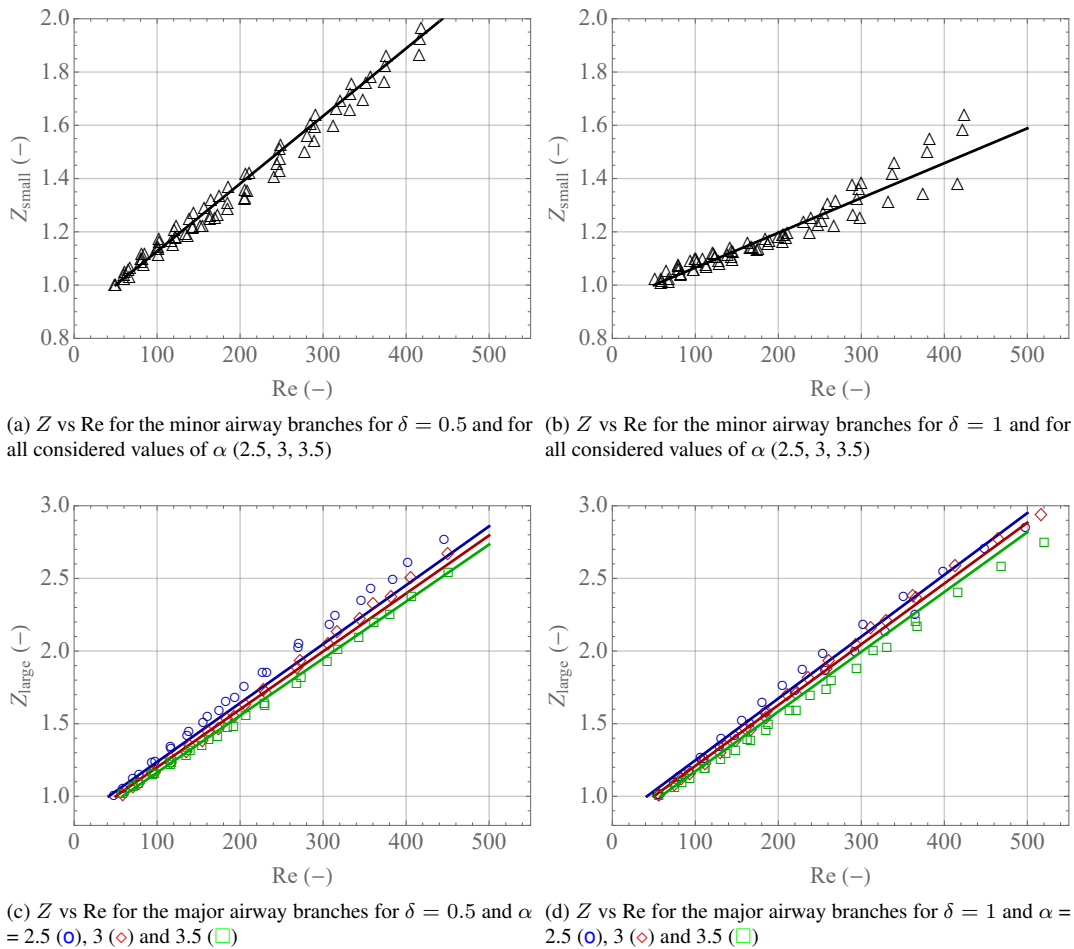


Figure 3: Simulation results (symbols) and corresponding correlations (full lines) for  $Z$  vs  $Re$  for the small airways (top) and the large airways (bottom). The graphs on the left correspond to an asymmetry of  $\delta = 0.5$  and the graphs on the right to an asymmetry of  $\delta = 1$ .

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