Pressure Losses on Realistic Geometry of Tracheobronchial Tree

Michaela Chovancova, Jakub Elcner

***Abstract*—**Real bronchial tree is very complicated piping system. Analysis of flow and pressure losses in this system is very difficult. Due to the complex geometry and the very small size in the lower generations is examination by CFD possible only in the central part of bronchial tree. For specify the pressure losses of lower generations is necessary to provide a mathematical equation. Determination of mathematical formulas for calculation of pressure losses in the real lungs is time consuming and inefficient process due to its complexity and diversity. For these calculations is necessary to slightly simplify the geometry of lungs (same cross-section over the length of individual generation) or use one of the idealized models of lungs (Horsfield, Weibel). The article compares the values of pressure losses obtained from CFD simulation of air flow in the central part of the real bronchial tree with the values calculated in a slightly simplified real lungs by using a mathematical relationship derived from the Bernoulli and continuity equations. The aim of the article is to analyse the accuracy of the analytical method and its possibility of use for the calculation of pressure losses in lower generations, which is difficult to solve by numerical method due to the small geometry.

***Keywords*—**Pressure gradient, airways resistance, real geometry of bronchial tree, breathing.

I. Introduction

THE analysis of pressure losses in the bronchial tree is important for the treatment of acute and chronic lung diseases. Distribution of drugs in the form of aerosols directly into the bronchial tree guarantees a rapid onset and maximum effect of the drug. Some medical substances should be transported to the top of the lungs other deeper into the lungs. Deposition of aerosols in human respiratory tract is influenced by its size, anatomy of the lungs, breathing pattern. This article is focused to analysis of airway resistance.

Primarily, it is necessary to understand the mechanism of breathing. The pressure gradient between atmosphere and alveolar region is necessary condition for airflow in the airways. Inhalation of air to the alveoli is secured by pressure in this area which is lower than the atmospheric, whereas the exhalation is achieved using reverse gradient. Variability in alveolar pressure is affected by lung expansion, which is driven by the movement of diaphragm and consequently by the ribcage enlargement. As a consequence, there is a decrease of the pleural pressure. This leads to an increase/decrease of transpulmonary pressure and thus to change of the lung volume. Inflating of the lungs is caused by the fact that the alveolar pressure is below atmospheric pressure. At the end of inspiration, the air stops flowing, because of balance between alveolar and atmospheric pressure.

Often way, how to analyse airflow in the bronchial tree are numerical simulations using computational fluid dynamics (CFD). Because of the complexity of real lung geometry, the airflow examination is possible only in limited number of generations of bronchial tree. A mathematical relationship is determined from Bernoulli and continuity equations to determine the behaviour of the pressure losses through lower generations. Article compares the results from CFD simulations with the results obtained using 1D equations based on above-mentioned mathematical relationship and evaluates the accuracy of the this method and the appropriateness of its use.

II. Geometry of Lungs

Inhaled air flows into the body through the upper respiratory tract, where is heated or optionally cooled and moisturized.

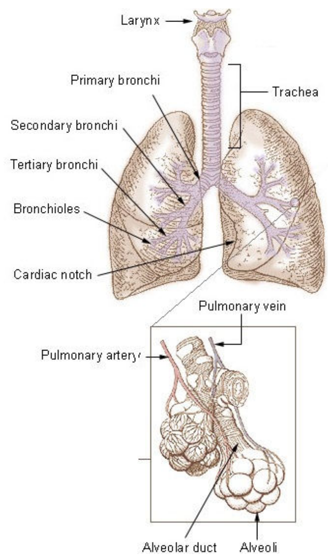

Fig. 1 Morphology of lungs [1]

Inputs through the mouth or nose and continues into the pharynx. The pharynx is divided into three parts, namely nasopharynx, oropharynx and laryngopharynx. The laryngeal part passes into the larynx. It is the borderline between the upper and lower airways. Larynx is then connected to the

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trachea. The air passes through the trachea, which enters to the chest where it branches into right and left bronchi. The bronchi changes after third generation of the branching to the bronchioles. Bronchial tree consists of about 23 generations. From the trachea to 16th generation of branching of bronchial tree is conductive part; from 17th to 19th generation is respiratory part where air is partially exchanged. 20th generation of the branching includes the alveolar ducts and they are terminated with alveolar sacs (23th generation). The alveolar sacs contain the alveoli, where respiratory gases between blood and air are exchanged using diffusion. Adult man has around 3 million alveoli [2].

The real lung has very difficult geometry compared to models of lung (Weibel, Horsfield). The cross-sections of branches in individual generation changing through its length but in the lung models are constant. The bifurcations do not branch in one plane only, but in all three directions. The geometry used in the calculation includes realistic geometry of the trachea and tracheobronchial tree up to 4th generation of branching. This geometry was obtained in the form of tabular data from the Institute of Anatomy and Cell Biology at the Justus-Liebig-University of Giessen in Germany. It includes the 17 generations (as Horsfield notation), but for our purposes, the model is finished in the third generation to the left side, and the fourth generation in the right lung (Fig. 2). The prepared human lungs were used for accurate derivation of geometry real lungs by CT with high resolution. The scanned lungs were withdrawn at autopsy to adult male and they were without pathological changes [3].

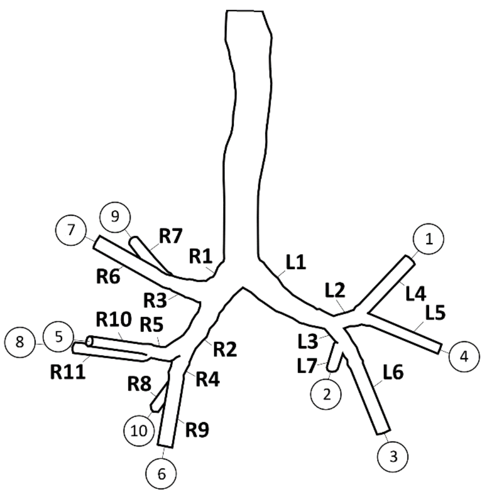

Fig. 2 Geometry of bronchial tree used in calculation

III. Numerical Setting

Numerical simulations were performed for inspiratory part of respiratory cycle. Geometry used for calculation consists of laryngopharynx, trachea and bronchial tree up to fourth generation of branching. Polyhedral mesh with 2.7 milions of cells (average size of control volume is 0.001 m) which contains prism layer for better prescription of near wall area were generated on this geometry. Case was calculated using unsteady RANS solver with hybrid SST-Menter model of turbulence [4] with corrections for low Reynolds numbers according to [5]. Airflow was prescribed according to realistic conditions inside lungs, where inspiration is driven from bronchial tree. On the outlets of the model (1 – 10), velocity inlet boundary condition with flat profile of velocity according to airflow in specific area was prescribed. Inlet to the model was treated with pressure outlet boundary condition with zero pressure resistance. Inspiration was driven by sinusoidal function according to (1).

$$v(t) = \frac{V_t \cdot \pi}{A \cdot T} \cdot sin\left(\frac{2\pi}{T} \cdot t\right) \quad [m.sec^{-1}] \qquad (1)$$

where $v(t)$ is velocity in time, V_t is tidal volume (0.5 l in this case), A is area and T is period (4 sec). Each step takes for 0.001 sec and the results were considered accurate under level of convergence of continuity under 1E-4.

IV. Method of Mathematical Calculation

If we want to solve pressure losses that arise during airflow in the airways, it is necessary to determine the flow regime, whether it is laminar or turbulent at first. For the breathing mode used in calculation is in all model laminar regime of flow.

Pressure loss of the airflow under laminar regime through a tube with the length L and radius r is determined by Poiseuille law

$$\Delta P_d = \frac{8L}{\pi r^4} \cdot \mu \cdot \dot{V} \text{ (Pa)} \qquad (2)$$

Pressure loss in the pipe under the turbulent flow regime is defined by

$$\Delta P_d = \lambda \cdot \frac{L}{d} \cdot \frac{v^2}{2} \cdot \rho \qquad \text{(Pa)} \qquad (3)$$

where frictional factor λ is calculated by Blasius empirical relationship. (d - diameter of the airways, v – velocity)

The local pressure loss is defined from the rate of flow $\dot{V}$: with density ρ, which flows from the tube of cross-sectional A_1 through an orifice area A_2

$$\Delta P_m = \frac{\rho}{2.C^2} \cdot \left(\frac{1}{A_2^2} - \frac{1}{A_1^2}\right) \cdot \dot{V}^2 \text{ (Pa)} \qquad (4)$$

The equation is derived from the Bernoulli equation. Conversion factor C is the discharge coefficient, which depends on the sharpness of the edge of the orifice and on Reynold number and has a value of about 0.6–0.7 [6].

Both turbulent and laminar flow cause a resistance to air moving in the airways and to overcome the resistance the pressure gradient/loss is needed. The airways resistance is measured in $cmH_2O/l/s$ and is defined as the ratio of the pressure difference to the airflow.

$$R = \frac{\Delta P}{\dot{V}} \qquad (cmH_2O/l/s) \qquad (5)$$

The value of the airways resistance during the resting breathing is around 1.5 – 2 cm H_2O/l/s. One would expect the major part of resistance, based on the Poiseuille law to be located in the narrow airways (the bronchioles), which have the smallest radius. However, measurements show that only 10% to 20% of total airway resistance can be attributed to the small airways (those < 2 mm in diameter). This apparent paradox results because so many small airways are arranged in parallel and their resistances are added as reciprocals. Resistance of each individual bronchiole is relatively high, but the large number of them results in a large total cross sectional area, causing their total combined resistance to be low [7], [8].

In a healthy person a major influence on the airways resistance has the lung volume change (generally when the lung volume increases the resistance decreases) and the breathing mode changes the flow rate.

V. Results

The calculation of pressure losses in the real bronchial tree had the same input parameters for numerical method and for analytical method. The input flow rate was 25 l / min which corresponding with forced breathing. The geometry described above was used for CFD simulation. The same geometry was applied for analytical method, but it was slightly simplified (the same cross-section in whole length of individual generation). The aim of this comparing is determine if the results from analytical calculation are approximately the same like the results from numerical calculation and thus whether it is possible the mathematical relationship used to calculate the pressure losses in the places of the bronchial tree, where the geometry is too small and thus numerical analysis too time consuming.

The central part of bronchial tree described on Fig. 2 (to 3th - 4th generation) has ten airways in total. All these paths were analysed by CFD and calculated by equation above (refer to (2) and (4)).

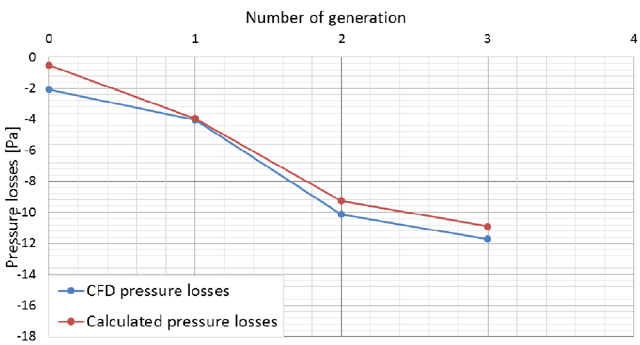

Fig. 3 Increase of pressure losses in airway 1

Fig. 3 shows the increase of pressure losses in airways number one (numbering of airways on Fig. 2). The red curve plots the increase of pressure losses obtained by analytical method and the blue curve by numerical method. As seen on figure, the results from the methods are for airway number one approximately same. Zeroth generation represents the pressure loss in trachea. There is a small difference between the two methods understandable. The difference arises, because the numerical calculation used the real geometry that mean the cross-section of trachea is changed in whole its length. In this case the pressure drop has two part, it is part of local losses to impacts of cross-sectional change and part of frictional losses. Trachea was considered as tube with constant cross-section over its whole length in the case of analytical calculation thus only frictional losses were considered.

The airway one and the airway four is passed to superior lobe in left lung. The airway number 4 has the similarly increase of pressure losses, because the larger part of its airway is the same like airway 1.

The similar behaviour as airways 1 and 4 has also airways 7 and 9. In these airways arise of relatively small differences between numerical and analytical method. There is the calculation formula valid.

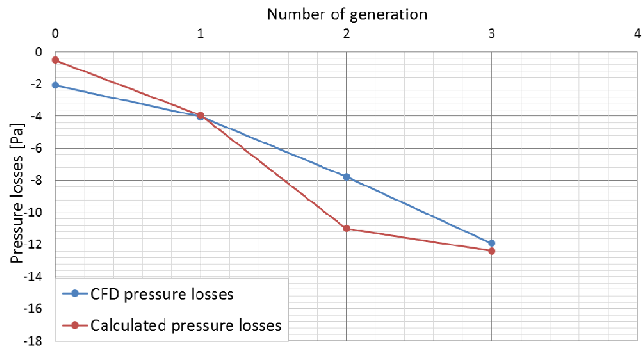

Fig. 4 Increase of pressure losses in airway 2

The airways 2 and 3 passed to inferior lobe in left lung. As seen on Fig. 4, there is small difference between compared calculation methods. The difference is about 3 Pa, which is otherwise a small value, we cannot ignore the difference in the small system like is bronchial tree. The airway 3 has up to second generation the same path like the airway 2 that means the same course of pressure losses. It is necessary to analyse the problematic bifurcation and identify the cause of the differences and then determine the correction factor.

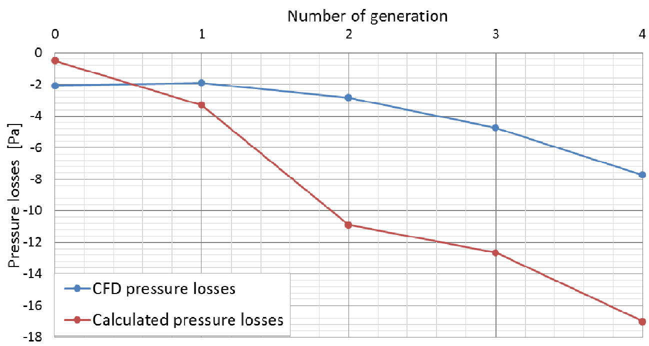

Fig. 5 Increase of pressure losses in airway 10

The significant difference between the analytical method and numerical occurred in the airways 5, 6, 8 a 10. All this ways have the same route to second generation. On Fig. 5 is a graph showing the increase of pressure loss in airway 10 (similar progress is in airways 5, 6 and 8). The considerable deviation occurs in the second generation, which is shared by all four routes mentioned above. Of course this difference has negative aspect to following progress of pressure losses.

After examining of the problematic bifurcation concludes that the deviation occur in places where the branching angle is 33° or less, i.e, in three generations in the central part of the bronchial tree. On Fig. 6 is seen the total pressure in the second bifurcation in the right lung obtained from the CFD simulation. It is a bifurcation in the central part of the bronchial tree, which has in crossing from R1 to R2 the smallest angle branching.

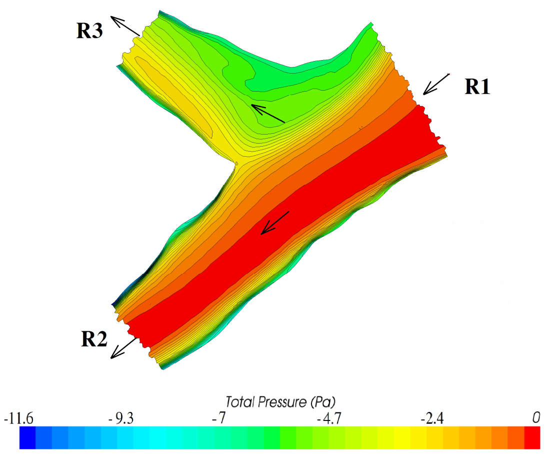

Fig. 6 Pressure losses in bifurcation R1-R2/R3

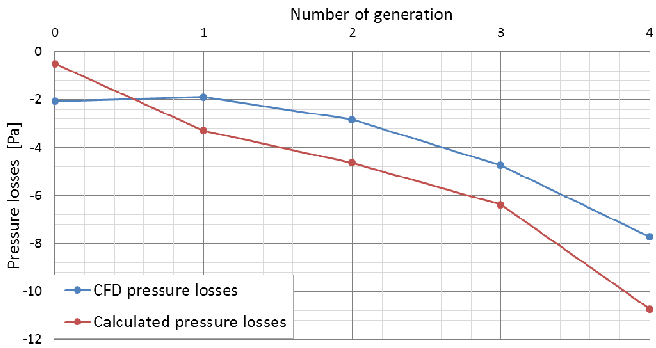

Fig. 7 Increase of pressure losses in airway 10 after modification

Equation (3) used for calculation solved the local pressure losses caused by sudden change in the cross section and the correction factor C takes into account the sharpness of the edge of orifice. As shown in Fig. 6 transition from R1 to R2 is almost direct and change of the cross section is not sudden but gradual. This fact may cause the difference. If we consider that the correction factor C was determined for bifurcation with Y-shaped with an angle greater than 33° and substantial impact on its value has a branching angle, it can be argued that the correction factor C approach in the case of transition from R1 to R2 to value 1. After this correction are the difference significantly reduced and the results of the analytical method are approaching to the results of CFD simulations.

VI. Conclusion

After comparing the numerical and analytical calculation of the pressure losses it was concluded that the mathematical relationship modified by constant C is valid for bifurcations, where the branching angle is greater than 33°. For other bifurcation is necessary to modify the correction factor C. The comparison made by reason to find out the suitability of use of the equation for calculating the pressure losses in such places in bronchial tree where the numerical method was due to the complex geometry of the extremely lengthy. So it is necessary the equation shall be applicable for terminal bronchioles. Horsfield model of lungs is a model which approximates to the real lungs. Horsfield describe the geometry of the central part of the bronchial tree and also the geometry of terminal bronchioles [9]. Approximately 90% of the terminal bronchioles have the branching angle more than 33°. It follows that in the terminal bronchi should be the mathematical relationship to a greater extent valid. The smallest angle of branching in this part of the lung is 30°. For this angle will be necessary to adjust the correction factor C.

In conclusion it can be said that the mathematical relationship derived from Bernoulli's equation and continuity equation modified by constant C is after comparison the analytical and numerical calculation suitable mathematical equation for calculation of the pressure losses in the places where it numerical method does not allow.

Acknowledgment

This article was supported by the project Excellent young researcher at Brno University of technology CZ.1.07/2.3.00/30.0039).

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