The Pressure Losses in the Model of Human Lungs

Michaela Chovancova, Pavel Niedoba

Abstract—For the treatment of acute and chronic lung diseases it is preferred to deliver medicaments by inhalation. The drug is delivered directly to tracheobronchial tree. This way allows the given medicament to get directly into the place of action and it makes rapid onset of action and maximum efficiency. The transport of aerosol particles in the particular part of the lung is influenced by their size, anatomy of the lungs, breathing pattern and airway resistance. This article deals with calculation of airway resistance in the lung model of Horsfield. It solves the problem of determination of the pressure losses in bifurcation and thus defines the pressure drop at a given location in the bronchial tree. The obtained data will be used as boundary conditions for transport of aerosol particles in a central part of bronchial tree realized by Computational Fluid Dynamics (CFD) approach. The results obtained from CFD simulation will allow us to provide information on the required particle size and optimal inhalation technique for particle transport into particular part of the lung.

Keywords—Human lungs, bronchial tree, pressure losses, airways resistance, flow, breathing.

I. Introduction

THE process of supplying oxygen to the human body and the removal of carbon dioxide is called breathing. The breathing is essential to life, so that to understand the mechanism of breathing is important in preventing diseases and also to select an appropriate method of treatment. Inspiration is the result of the pressure difference between alveolar pressure and atmospheric pressure, i.e. the pressure in the mouth or nose. The negative alveolar pressure develops with lung expansion, which is triggered by pressing the diaphragm downward and consequently the ribcage is enlarged. As a consequence, there is a decrease of the pleural pressure. It produces an increase of the transpulmonary pressure and so the lungs are inflated. Inflating the lungs causes the alveolar pressure drop below atmospheric pressure. Airflow stops at the end of inspiration, because alveolar pressure is again in balance with atmospheric pressure.

One of the methods to study the airflow in the lungs is using CFD. Because of complexity of the lungs geometry, the CFD calculations are limited to upper tracheobronchial airways and thus we need as correct as possible outlet boundary conditions at the terminating airways. A standard approach, which is mostly used, is to prescribe zero pressure. Another way how to set up the most realistic airflow in the model is based on the pressure difference between the inlet and terminal outlets. Our task was to determine the pressure at the end of individual terminating branches.

Pressure drop is directly related to the resistance of the airways. Airways resistance is defined as a ratio of driving pressure and the rate of air flow. Resistance to flow in the airways depends on whether the flow is laminar or turbulent, on the dimensions of the airway and on the viscosity of the gas.

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II. Geometry of the Lungs Used in the Calculation

The airways begin in nasal or oral cavity from where the air flows to the pharynx. The pharynx is divided into three parts, namely nasopharynx, oropharynx and laryngopharynx. The laryngeal part passes into the larynx. It is the boundary between the upper and lower airways. Trachea connects to the larynx. 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 23 generations. From the trachea to 16_{th} generation is conductive part; from 17_{th} to 19_{th} generation is respiration part where air is partially exchanged. 20_{th} generation of the branching includes the alveolar ducts and they are terminated with alveolar sacs (23_{th} generation). The alveolar sacs contain the alveoli [5].

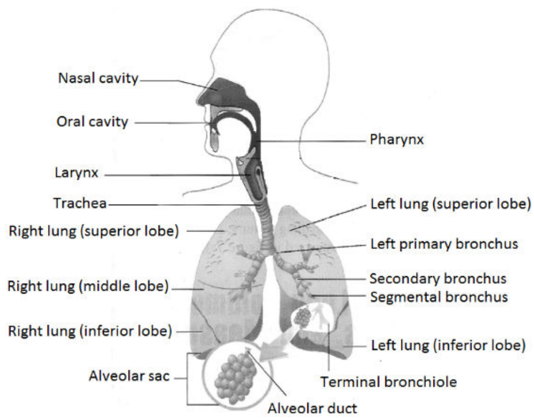

Fig. 1 Morphology of human lungs [3]

In view of the fact that each person has a different geometry of the lungs (depending on age, gender, body composition, weight, height) for calculation purposes several models of the lung are used. The simplest model of the lungs is a Weibel symmetrical model, i.e. all ways from trachea to alveoli are the same and all branching are at the same angle [4].

The model of the bronchial tree which is closer to the real lungs was proposed by Horsfield. He created two lungs models on the basis of the measurements on prepared human lungs. It was the healthy lungs of 25 years old man. The lungs were inflated to volume 5 liters and prepared be using of resin cast. Subsequently, all structures greater than 0.7 mm were measured. The smaller structures were separated and measured separately until to the respiratory bronchioles. The data were then processed by computer [6], [7].

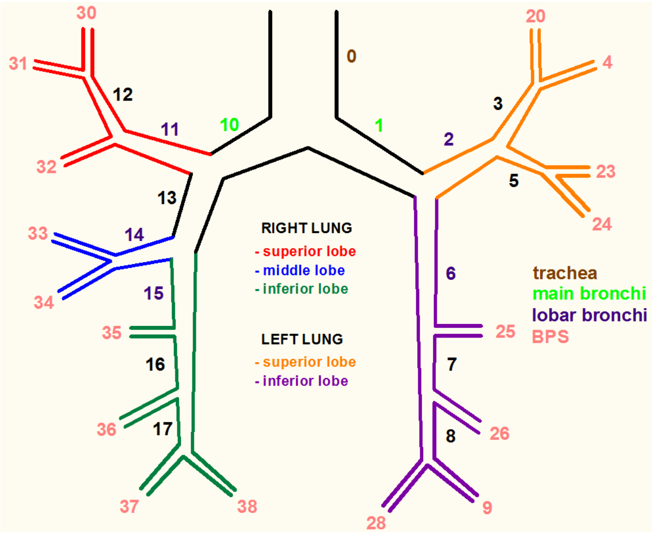

Fig. 2 Horsfield's model of human bronchial tree

The both Horsfield models have the same central bronchial tree (Fig. 2) but in the first model asymmetry is described for each lobe separately and in the second model the geometry is described for each bronchopulmonary segment (BPS) separately. Seventeen bronchopulmonary segments are divided into three group in accordance with the branching ratio. Each group has its mathematical equation. The airways dimensions are given for every BPS separately. Our calculations were performed with the second Horsfield model.

The numbering of the central bronchial tree (Fig. 2) is by number of branch and begins with 0 for trachea and ends with 38. BPSs are assigned of an order number. The longest BPS ways begin with the order 25. All ways in the model two terminate with the order 7.

On the basis of the above described input data a mathematical model in MATLAB was developed, which determines all airways from the trachea to the order 7. It is conductive zone of the bronchial tree for which the mathematical equations described below are valid. Model calculates the pressure losses for 2536 airways, which are all airways in conductive area of the Horsfield model.

III. Capacity of Horsfield's Lungs

The total lung capacity of the Horsfield model is not defined in his publications, so we will consider the same total capacity as in the Weibel lungs, i.e. 6400 ml. The most literature sources indicate the total lung capacity 6000 ml and lung volumes result from this value. If these values are applied to the total volume of 6400 ml, the functional residual capacity is around 2600ml (Fig. 3). It is the volume after quiet exhalation, ergo in the beginning of the respiratory cycle. The quiet inhalation increase capacity about 500 ml, so the lung volume after the quiet inhalation is 3100 ml. As mentioned above, the Horsfield lungs are inflated to the 5000 ml. Suppose that this is the capacity after the forced inhalation (FI). It follows from this that before the inhalation starts; the lung volume of 2400 ml is taken from the lungs volume.

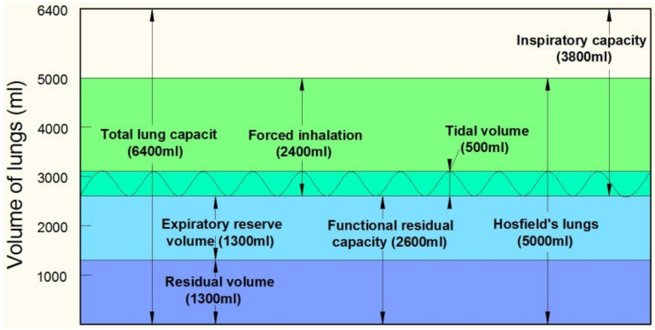

Fig. 3 Capacity of Horsfield's lung

It is assumed that each generation in the bronchial tree have the same elasticity besides trachea and primary bronchi due to the presence of the cartilages. During the inspiration/ expiration mainly the cross-section is changed. Their length change is negligible and has not effect on the airways resistance, therefore this change is not considered in the calculation. The cross-sections of the airways before inspiration are determined from the volume of the airways at the beginning of the respiratory cycle. Similarly are determined the dimensions of the airways with lung volume 3100 ml (after quiet inspiration).

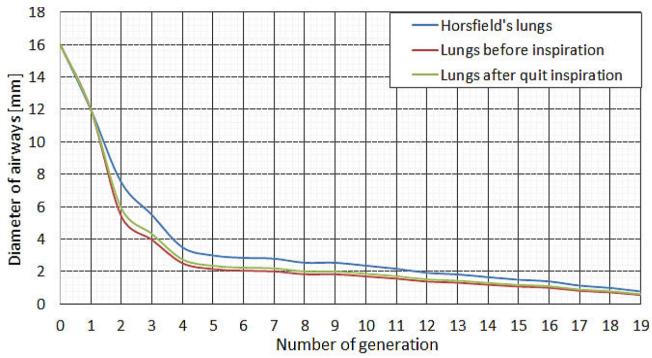

Fig. 4 Dimensions of the airways

IV. Method of Calculation

If we want to solve pressure losses that arise during air flow in the airways, at first it is necessary to determine the flow regime, whether it is laminar or turbulent. During the resting breathing with the flow rate 15 l/min and the tidal volume 0.5 l, only laminar flow appears. The maximum value of the Reynold number is in the trachea and is 1270. During the forced inspiration with the airflow 60 l/min and the tidal volume 2.2 l turbulent flow arises in trachea and primary bronchi.

Pressure loss of the air flow for laminar regime through a tube of the length L and radius r is determined by Poiseuille law

$$\Delta P_d = \frac{8L}{\pi r^4} \cdot \mu \cdot \dot{V} \text{ (Pa)} \tag{1}$$

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

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

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

$$\Delta P_m = \frac{\rho}{2.C^2} \cdot \left(\frac{1}{A_2^2} - \frac{1}{A_1^2} \right) \cdot \dot{V}^2 \text{ (Pa)} \tag{3}$$

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 [1].

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.

$$R = \frac{\Delta P}{\dot{V}} \qquad (cmH_2O/l/s) \tag{4}$$

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 [2].

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 results are analyzed and processed in the same way as the calculations for Weibel model for the later comparison of results from both, Weibel and Horsfield models. The pressure loss is calculated for:

a) **Quiet breathing** corresponding to the airflow 15 l/min and the tidal volume 0.5 liters.
b) **Forced breathing** with the flow rate 60 l/min and tidal volume 2.4 liters.

All airways in conductive region of Horsfield lungs model are analysed and pressure losses are calculated are in MATLAB. Mathematical equation to calculate local pressure losses is derived from the Bernoulli equation and takes into account the impact of changes in cross-section. Other aspects such as flow splitting, change in the direction of the flow and radius of curvature are not considered. For Weibel simplified symmetrical model results are satisfactory. But in the case of more complex Horsfield geometry (daughter branches with different cross-sections, different branching angles, and radius of curvature) the results in some airways of the bronchial tree are overpredicted.

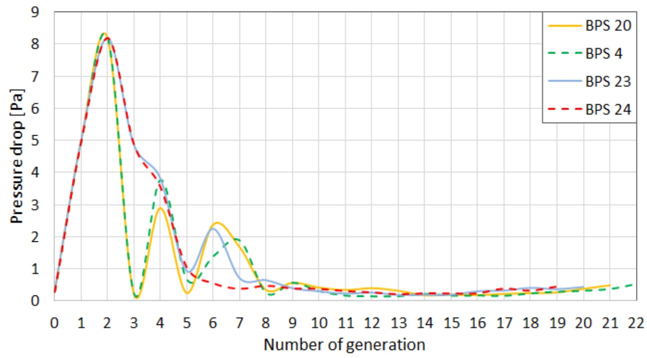

Fig. 5 Pressure drop in the longest airways of BPS 20, 4, 23, 24.

Fig. 5 shows pressure losses in the longest airways in four bronchopulmonary segments, namely 20, 4, 23, and 24 of the left upper lobe. BPS 23 and 24 show an acceptable course with a peak in the second generation and a successive decrease. BPS 20 and 4 also have a peak in the second generation, but a significant decrease in the 3rd and 5th generations does not correspond to real values. This error arises because of the mathematical relationship used in the calculation, based mainly on the change in the cross section. In these two generations a significant change of the cross-section appears. For the correct results, it is necessary to establish correction factors that would take into account other aspects causing pressure drop in bifurcations.

Fig. 6, results of an analysis are shown that uses a moving average function. With this function values of local pressure losses are corrected. As can be seen in the graphs, the pressure losses reach a steady value from 9th generation. From this segment on, linear pressure losses according to Poiseuille law play more important role than the local pressure losses, so that its correction almost does not affect the final pressure losses.

The pressure losses of the BPS 20 and 4 (Fig. 6) have after correction the course corresponding to real course. Using the same approach all airways in the conductive area of the bronchial tree are analyzed.

The above correction is used for a preliminary evaluation of the results. These will be later analysed and compared with values obtained from CFD simulations of a realistic lung model. The purpose will be to determine correction factors.

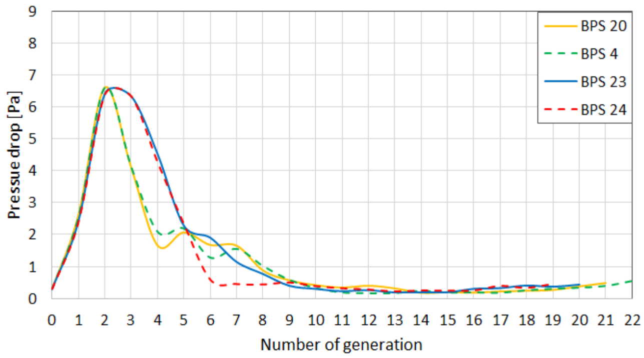

Fig. 6 Pressure drop in the longest airways of BPS 20, 4, 23, 24 after correction

In Fig. 7 is seen the progress of the pressure losses during quiet inspiration in the longest airways (BPS 24) of the left lung (branches in the central part 0, 1, 2, 5, 24 and orders in BPS from 21 to 7). The blue curve represents the course of the pressure losses through static airways prior to inhalation for lung with the volume of 2.6 l. The green curve is the static pressure losses for lung volume of 3.1 l. During inspiration the gradual increase of the lung volume occurs and so does the cross-section of airways. It means that we can assume that the pressure loss during the inhalation should be somewhere between these curves. It is shown as the red curve. As seen more significant pressure drop occurs in generations prior to 6th generation of branching. In these segments also the largest changes of the pressure losses caused by the volume changes arise. Then the pressure losses are almost constant and do not change significantly due to changes in the volume or by moving to the next generation.

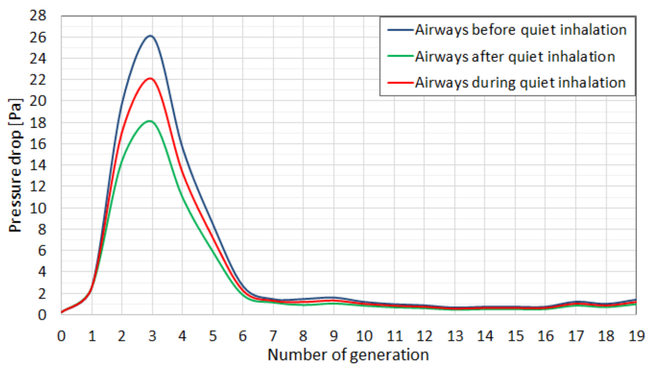

Fig. 7 Pressure drop in the airways during quit inhalation

In Fig. 8 can be seen that the change of lung volume affects mainly the local losses. Linear losses change only minimally by the change of the lung volume. It is also obvious that in the terminal bronchiole from 7th generations on the linear losses given by Poiseuille law have larger effect than the local losses.

On Fig. 9 the comparison of the longest way and the shortest way of the BPS 24 is shown. The shortest way has only 7 generations, five branches in the central part of the bronchial tree (0, 1, 2, 5, 24) and only three orders in the BPS (17, 12, 7). Considering that all paths in BPS 24 have the same central part, the course of the pressure losses in this area is the same. The change occurs in individual orders of BPS where the pressure losses increase. The total pressure losses of the longest way of the BPS 24 during the inhalation are 77 Pa and of the shortest are 74 Pa.

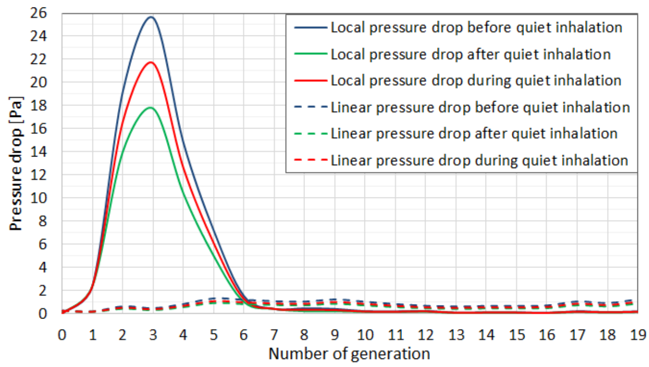

Fig. 8 Local and linear pressure drop in the airways during quit inhalation

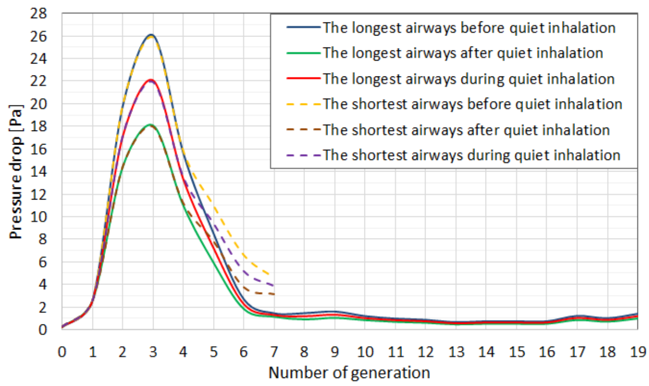

Fig. 9 Pressure drop in the airways during quit inhalation in the longest and the shortest airway in BPS 24

A similar progress as BPS 24 have all paths of the Horsfield bronchial tree, where the stabilization of pressure losses begin around 9th generation of the branching. A total pressure loss of the most airways during quiet inspiration is approximately the same and is around the value of 75 Pa (± 10 Pa). The largest deviation from reality arose in BPS 33, 34, 35 and 36, where the value of the total pressure losses during resting inspiration is from 114 to 177 Pa. This deviation is caused by neglecting all factors connected with bifurcation. To find an appropriate correction factor will be the next task.

After analysing resting breathing pressure losses during forced inhalation are calculated. The lungs after the forced inspiration (FI) increased its volume to 5 l (Horsfield lungs). The input airflow is 60 l/min. The calculations are processed in the same way as for the quiet breathing, i.e. for static lungs at the beginning of the inspiration (volume 2.6 l) and for static lungs after the inspiration (volume 5 l), and the mean value which represents an approximate course of the pressure losses during the inspiration.

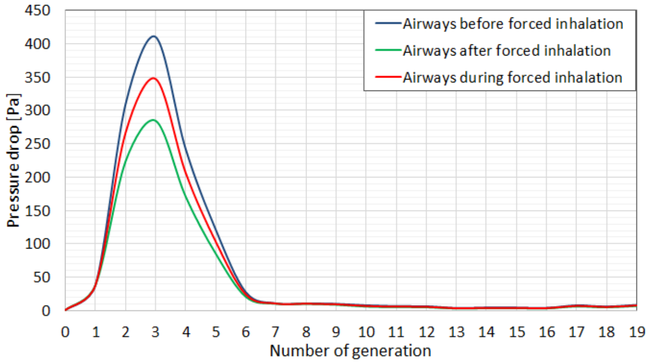

Fig. 10 Pressure drop in the airways during forced inhalation

The pressure drop in BPS 24 due to the increased input airflow very markedly increases. The highest value of 350 Pa is in the 3rd generation during inhalation (Fig. 10). The total pressure losses in BPS 24 during forced inhalation are 1044 Pa. In the other airways of bronchial tree pressure losses have a similar trend as during the quiet breathing except BPS 33, 34, 35 and 36, where total pressure loss is significantly higher, namely from 1590 to 2590 Pa. In the whole bronchial tree the highest pressure losses are reached in 3rd and 4th generation and the stabilization begins around 9th generation of the branching.

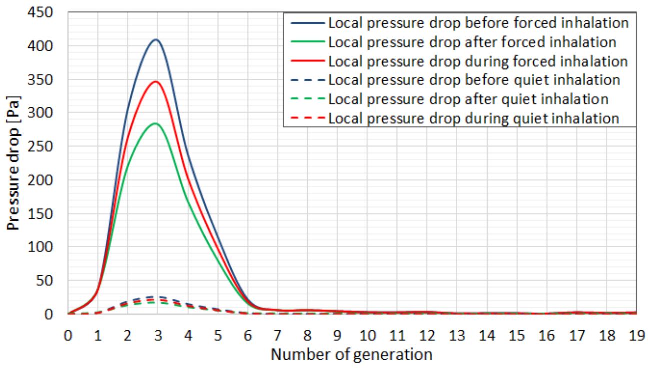

Fig. 11 Local pressure drop in the airways during quit and forced inhalation

The change of input airflow mostly altered the local pressure losses in the generations from 1 to 6 (Fig. 11). In these segments pressure losses increased from 17 to 320 Pa. In the 10th – 19th generation the increase is only about 2 Pa in each generation (see detail in Fig. 12).

The increment of the linear losses due variation of the input airflow is not very strong given the total pressure losses in the airways. The change in each generation of the bronchial tree is in the range from 0.6 to 4 Pa (Fig. 13).

Airway resistance also reached their highest levels in central part of the bronchial tree. The value starts be stable from the 8th generation and there the differences between the two respiratory cycles begins be minimal.

According to the literature airway resistance during the quiet inhalation should be around values from 1 to 2.5 cmH_2O/l/s. From our calculations, we obtain the value of 3.1 cm H_2O/l/s, which can be considered as an acceptable result. For the forced inhalation a value of 11 cmH_2O/l/s is obtained, which is already relatively high number.

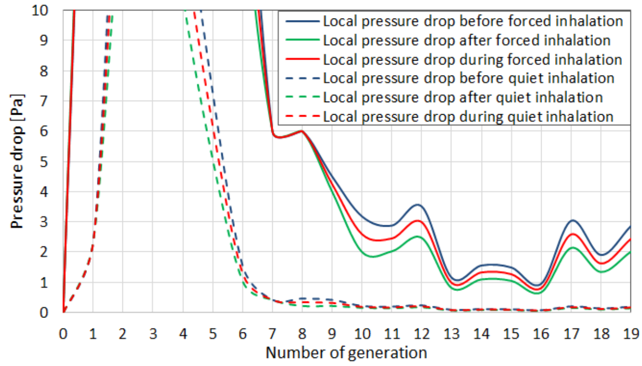

Fig. 12 Local pressure drop in the airways during quit and forced inhalation - detail the terminal bronchiole

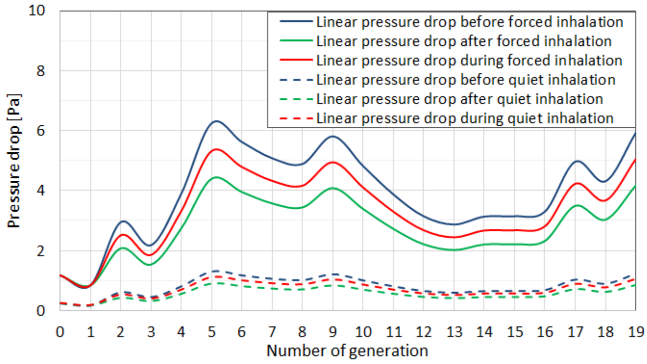

Fig. 13 Linear pressure drop in the airways during quit and forced inhalation

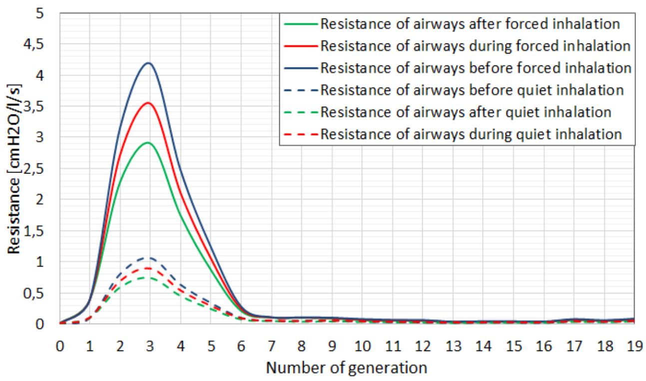

Fig. 14 Resistance of airways

VI. Conclusion

Calculation of pressure losses during quiet inspiration in Horsfield bronchial tree, using Poiseuille law for the expression of linear losses and using the equation derived from Bernoulli equation for expression of local losses, proved to be satisfactory. Horsfield second model ends by 7th order; it is the last generation of conductive area. Pressure losses should be there for all airways approximately the same, considering that the alveolar pressure in the lungs should be the same (from the 7th order to the alveoli is diffusion region, there should rather occur to partial change of pressure than the pressure drop). In our calculations arose in the four BPS significant differences of the total pressure losses compared to other airways in the bronchial tree. The reason for these deviations is that the mathematical formula used to calculate the pressure loss in the bifurcation takes into account only the change in the cross-section and via a correction factor C the effect of Reynolds number, but not the flow splitting and branching angle.

Literature specifies range of airway resistance during resting inhalation from 1 - 2.5 $cmH_2O/l/s$ [5]. The most of the airways in the model of the human lungs had a value of about 3 $cmH_2O/l/s$. Our results can be considered satisfactory.

During forced inhalation relatively high values of pressure drop were obtained. Pressure loss in most of airways in the bronchial tree oscillates around 1 kPa. This value seems be high for such a small pipe system (the longest way is around 31 cm), but on the other hand considering the number of branching it seems possible. Airways resistance is up to 11 $cmH_2O/l/s$. These results are comparable with other published results. Correctness of our calculations may be checked by comparing with the results in Weibel simplified model. In this case the agreement is quite acceptable. Airway resistance during quiet inspiration is 1.2 cm H_2O /l/s and during forced inhalation is 3 $cmH_2O/l/s$. Given that the result for the quiet inhalation is in the range indicated by literature, the resulting value of 3 cmH_2O/l /s for forced inhalation can be deemed for a value approaching reality. Thus, the resulting value of the Horsfield lungs seems relatively high.

To obtain better and more accurate results, it is necessary to use a more sophisticated mathematical formula for the calculation of the pressure losses in the bifurcations, or to find a correction factor that takes into account all aspects that affect the pressure loss in the bifurcation. This will be the subject of our next work.

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