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NUMERICAL SIMULATION OF AIR FLOW IN REALISTIC MODEL OF HUMAN UPPER AIRWAYS

NUMERICKÁ SIMULACE PROUDĚNÍ V REALISTICKÉM MODELU HORNÍCH CEST DÝCHACÍCH

Abstract

This article deals with CFD calculations of flow patterns in a realistic model of the upper respiratory tract. RANS method was used for the calculation. The flow was solved as an unsteady one due to its nature. Two breathing cycles were simulated, 15 l/min which corresponds to the idle breathing mode and 30 l/min which corresponds to light activity. The model of upper airways consists of the oral cavity, larynx and trachea, which branches up to the fourth generation. Values of the velocity field distribution calculated are the basis for future calculations of aerosol transport and deposition in the human respiratory tract.

Abstrakt

Tato práce se zabývá CFD výpočtem proudových polí v realistickém modelu horních cest dýchacích. Pro výpočet byla použita metoda RANS. Vzhledem k povaze proudění byl výpočet řešen jako nestacionární. Simulovány byly dva režimy dýchání, dechový objem 15 l/min, který odpovídá klidovému režimu dýchání a 30 l/min, který odpovídá lehké aktivitě. Model horních cest dýchacích sestává z ústní dutiny, hrtanu a trachey, která se dále větví až do čtvrté generace větvení. Vypočtené hodnoty rozložení rychlostních polí jsou základem pro budoucí výpočty transportu a depozice aerosolů v dýchacím ústrojí člověka.

1 INTRODUCTION

Accurate geometry is one of the main prerequisites for obtaining real results of airflow in the human upper airways. Ewald R. Weibel was a pioneer in the development of lung models, who laid the foundations of lung morphometry through his work [1] and defined the one of the first models nowadays called after him - Weibel lung model. This model consists of symmetrical branches, whose geometry is simplified to cylinders arranged in a single plane. Another popular model is the Horsfield model [2] which differs from the Weibel model in asymmetric branching, considering location of the heart within the human body. Therefore, the left branch in the first generation is longer than the right one and the model also provides spatial orientation of each branch. Recently, these idealized models have been abandoned, and, for numerical calculations [3] as well as experimental measurements [4],

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models obtained with the use of methods based on the computer tomography and magnetic resonance imaging gained in popularity. These models provide accurate geometrical information about the spatial arrangement of the respiratory tract.

2 MODEL

The presented geometry, used for numerical calculation of the airflow, is based on several separate models, namely, the model of oral cavity, the trachea model and the model of bronchial tree up to seventeenth generation of branching. The model of the oral cavity, including a part of the trachea, was obtained from the Lovelace Respiratory Research Institute in Albuquerque (USA) [5] as a wax model which was later on 3D digitized and converted into a stereolithographic format (.stl). The trachea geometry was acquired from the Faculty Hospital St. Anna in Brno which employed computer tomography (CT) for the task. Only the part missing between the oral cavity and bronchial tree was applied from this geometry. The bronchial tree model came from the institute of Anatomy and Cell Biology at the Justus-Liebig University in Giessen (Germany) [6]. The necessary modifications to it were done by prof. Premysl Krska from Faculty of Information Technology at the Brno University of Technology. Two versions of the model were made for the purpose of numerical calculations and experimental measurements. First version included the oral cavity fitted with an extended mouth nozzle, trachea and bronchial tree to the fourth generation of branching. The second version of the model extends the first one to the seventh generation of branching of the bronchial tree. The first version of the model was used for the calculations appearing in this article. The individual parts of the model are shown in the figure 1. The lengths and diameters of branches are shown in table 1.

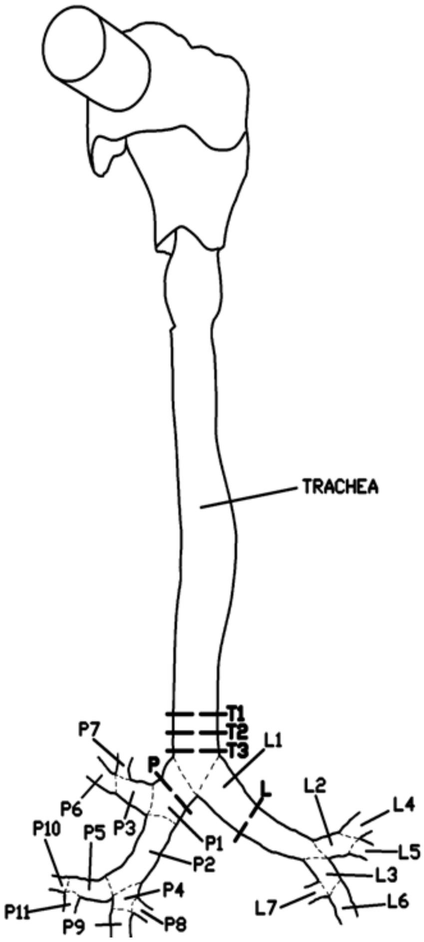

Fig. 1 Model parts description

Tab. 1 Lengths and Diameters of single branches

Left side			Right side		
Branch	**Length (mm)**	**Diameter (mm)**	**Branch**	**Length (mm)**	**Diameter (mm)**
L1	42	10	P1	13	13
L2	16	6	P2	24	9
L3	7	6	P3	21	8
L4	3	6	P4	6	8
L5	6	5	P5	14	6
L6	10	6	P6	6	8
L7	9	5	P7	9	6
			P8	7	5
			P9	4	7
			P10	4	5
			P11	8	4

3 METHODS

The calculation was performed using commercial software StarCCM+. The model was placed in the program so that the tracheal axis parallel to the axis Z of the Cartesian coordinate system. The origin of the coordinate system was located at the inlet to the mouth nozzle in the axis of the cylinder, which forms the nozzle. Location of the cross section through the trachea and selected branches are shown in figure 1.

The mesh was built using the generator integrated in StarCCM+. It contains approximately 2.2 millions of tetrahedral cells. The core tetrahedral mesh was transformed into a prismatic layer of cells in the near wall region to improve the solution accuracy of the boundary layer. Volumetric flow rate was specified at the mouth entry by means of the velocity profile. Total pressure was imposed at the ends of the branches. The simulation was run as a transient one with the use of the k-omega turbulence model. The results were considered converged when residuals dropped below 10^{-4} limit.

Two breathing regimes were considered. In the first case, which corresponds to the idle mode of breathing 15 l/min of air were supplied through the mouth nozzle. In the second case, corresponding to the light activity the value changed to 30 l/min. With the size of mouth nozzle of 20 cm these amounts corresponded with the velocity of 0.8 m/s (Re = 1054) and 1.6 m/s (Re = 2108), respectively. Laminar profile was set as a velocity profile entering to the mouth nozzle.

4 RESULTS AND DISCUSSION

The calculated results show us the distribution of velocity fields. Figure 2 shows a comparison of the velocity profiles depending on the flow rate of 15 l/min and 30 l/min in the trachea, close to the first branching (bifurcation) of the bronchial tree.

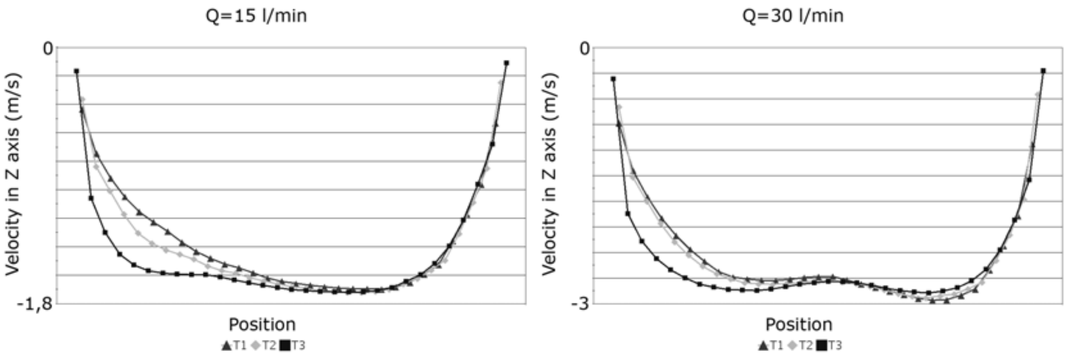

Fig. 2 Comparison of velocity profiles in trachea, before first bifurcation

At the air flow of 15 l/min, the air speed reaches 1.8 m/s in the opposite direction to the Z axis. The magnitude of the Reynolds number at this air speed correspond to Re = 2384 and the graph in figure 2 shows that the velocity profile is nearly turbulent. It can be seen that the velocity magnitude on the right side of the profile is lower than on the left side. This phenomenon is probably caused by the shape of the trachea, which is not a direct channel of a circular profile. Lower velocity may also be caused by greater resistance to the flow on the right side of the model (description to the left and right sides of the model is based on conventions established in medical literature and corresponds to the lungs in humans relative to the perspective of a man, the right side is near the right hand).

The flow through mouth nozzle at the second breathing regime was set to 30 l/min. This time the air speed reached maximum of 3 m/s towards the Z coordinate. There is an apparent decline of velocity magnitude near the channel centre. This decline is probably caused by the resistance of the first bifurcation of the bronchial tree, in which the flow of air from the trachea impinges to the lower edge of bifurcation and divides into two streams which then enter the left and right branches of the model.

Other significant differences between the idle mode and the mode corresponding light activity were not observed, therefore the results for the idle mode only will be further presented. Figure 3 depicts the flow field in the first generation of branching (trachea is considered to be the zero generation) of the bronchial tree.

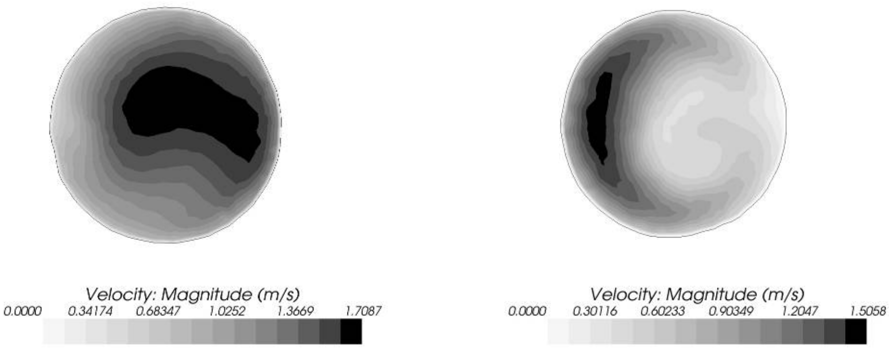

Fig. 3 Cross-section through branch, Q = 15 l/min: on the left = P section, on the right = L section

Although the two cross-sections are the first generation of the bronchial tree and the first branching angles approximately symmetrically, the shape of velocity profiles is very different. While for the branch P1, the shape of the profile is approximately symmetrical and greatest velocities occur near the center of the channel, in the middle of the jet which passes through the branch L1 the air speed reaches it minimum; the maximum speeds are located at the bottom of the branch. This variability, probably due to the shape of the branch could have great influence on the deposition of solid particles at the bottom of the branch.

Figure 4 is a section of the oral cavity and trachea. The important part of the picture represents the so-called laryngeal jet. It is an increase in air speed caused by the airflow around the larynx. The impact of this phenomenon on the flow and particle deposition is described in more detail in [3].

Fig. 4 Oral cavity and trachea

5 CONCLUSIONS

Flow field calculations performed with the use of a realistic model of the upper respiratory tract is an important step in further research on the transport and deposition of aerosols in the respiratory tract of man. In the future, a new experimental model is going to be created with the same geometry as the one used within this article so the results of calculations can be compared with those of experimental measurements.

ACKNOWLEDGMENT

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