Investigation of air flow in idealized model of human respiratory tract

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Abstract Validation of numerical simulation using experimental data is necessary prerequisite for authentication of proper use of numerical method. This article deals with comparison of velocities on idealized model of human upper airways during stationary inspiration for three different breathing regimes. For the purpose of this study, the model which includes realistic geometry of mouth cavity and glottis coupled with idealized geometry of trachea and bronchial tree up to fourth generation of branching was made. Calculations were compared with experiments acquired by Phase-Doppler Particle Anemometry (P/DPA) on identical geometry. Velocity data were compared at several points in trachea and bronchial tree. Specific air flow characteristics are documented and discussed based on results of the numerical simulation of the velocity field.

1 Introduction

Breathing is a complex phenomenon which represents a flow of the air through system of channels called respiratory tract. Inspiration is initiated by movement of diaphragm and resulting pressure difference which is caused by volume change of air paths in bronchial tree. Due to this pressure difference, air flows through mouth cavity, larynx, trachea and bronchial tree into the alveolar region, where blood is enrich by oxygen and gets rid of carbonate dioxide. After that, deoxidize air is conducted during expiration, through the same path as it comes and is exhaled to atmosphere. During this path, the character of air flow is constantly affected by physiological and anatomical factors. Most of factors which affects the flow characteristics can be observed in trachea. A first phenomenon, visible on the beginning of trachea, is studied by Lin [1] and it is called laryngeal jet. Laryngeal jet is caused by constriction of air path in larynx, where velocity and turbulent kinetic energy grows and shape of velocity profile is strongly affected. Second phenomenon is caused by first bifurcation at the end of trachea. This bifurcation changes the shape of velocity profile, during inspiration, in distance of several diameters of trachea before bifurcation itself. A phenomenon's mentioned above can be investigated by *In vivo*, *In vitro* or *In silico* methods. *In vivo* methods are not commonly used nowadays for ethical reasons and for its demanding measurements. *In vitro* methods, for example High Resolution Computer Tomography (HRCT), Laser Doppler Velocimetry (LDV) or Phase Doppler Particle Anemometry (P/DPA), are commonly used, but complicated geometry of bronchial tree make measuring in the highest generations of branching very difficult and it does not give us complete idea of flow in lungs very often. If we want to know the character of flow fields in these parts, the best way is CFD calculation validated by *In vitro* measurement, which completes whole image of air flow in human respiratory tract.

2 Model

Main reason for design of the idealized model (**Fig. 1**) is to obtain more realistic image of flow characteristics inside trachea and early generations of bronchial tree. Experiments performed on the model are made by using P/DPA technology whose accuracy is dependent on material used for fabrication and shape of geometry which surrounds a measured point. Therefore, combination of realistic and idealized geometry was selected. Upper part of the model (mouth cavity and larynx) and particular bifurcations, where realistic geometry is required for better development of airflow, are made by rapid prototyping method which allowed us to create arbitrary shape of airway with respect to a characteristic wall curvature which can be found on real human airways. Rest of the model (trachea and branches of bronchial tree) was made by thin-walled glass tubes. Length and diameter of particular branches was determined with respect to similarity with realistic model formerly used during measurements on Department of Thermodynamics and Environmental Engineering of Brno University of Technology [2]. Angles of branching were also determined from the realistic model by measure of angles which is hold by daughter branches in single bifurcation. More information about development of the model used for this study can be found in [3].

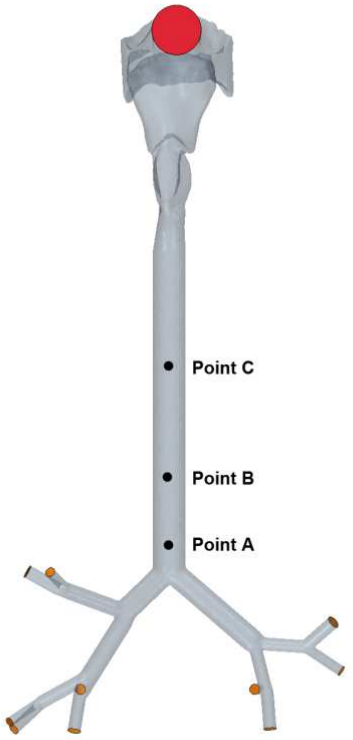

Fig. 1 Idealized model

3 Experiment

The experiment was performed using P/DPA technique. The model was connected to a pneumatic mechanism which simulates breathing cycle for three different breathing regimes (see **Tab. 1**). The measurement was made in 3 points in axis of trachea. First point (in direction of inhalation) was situated under larynx, second point was situated in the centre of trachea and third point was laid at the end of trachea before first bifurcation. A velocity component in direction perpendicular to the cross-section of the trachea (expected direction of air flow in the model) was measured. More information about the measurements can be found in [4].

Tab. 1 Investigated breathing regimes.

Activity	Q (l/min)	V_t/T (l/s)	Re
Resting condition	15	0.5/4	1404
Deep breathing	30	1/4	2809
Light activity	60	1.5/3	5618

4 Calculation

The calculations were performed by CD-Adapco StarCCM+ software. Orientation of the model fits the lungs position in the human body. Tracheal axis was parallel to the Z axis of the global coordinate system and the input into the model lies in the plane formed by the X and Z axis.

Computational mesh consists of polyhedral cells and contained approximately 2,000,000 cells. A prismatic layer was developed on the model wall for better description of the flow in the boundary layer. Unsteady RANS solver with k-omega turbulence model was used for the calculation. Velocity inlet condition prescribed by time-dependent equation (1), which simulates the breathing cycles corresponding to the breathing regimes mentioned in **Tab. 1**, was set on the input to the model and pressure outlet condition was set at the end of the branches.

$$Q(t) = \frac{V_t \cdot \pi}{T} \cdot \sin\left(\frac{2\pi}{T} \cdot t\right) \quad (m^3 \cdot s^{-1}) \tag{1}$$

Where Q is flow rate, V_t is tidal volume in m^3.

All the points which were measured in the experiment were monitored during the calculation.

5 Results and discussion

Comparison of measured and calculated values for three different points in trachea and three different breathing regimes according to **Tab. 1** is shown in **Fig. 2-4**.

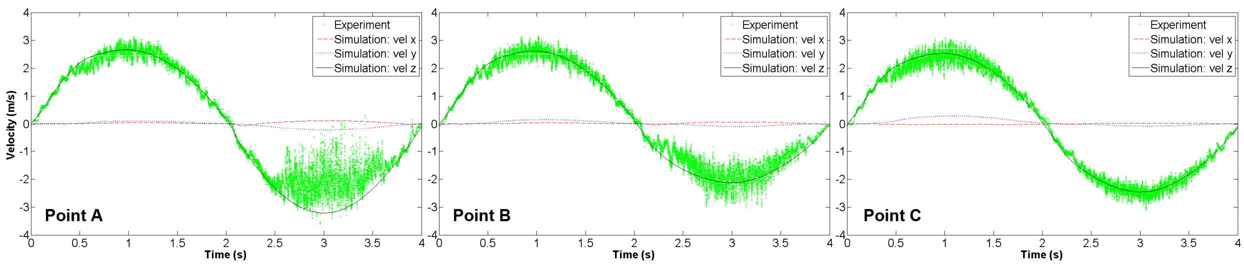

Fig. 2 Comparison of measured and calculated velocities for resting condition

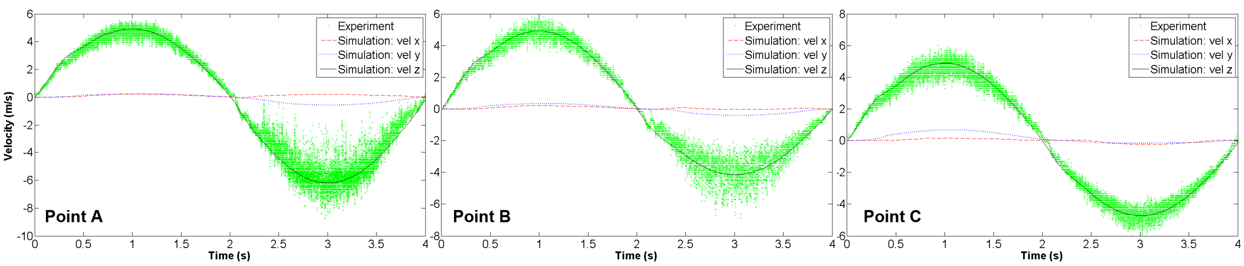

Fig. 3 Comparison of measured and calculated velocities for deep breathing

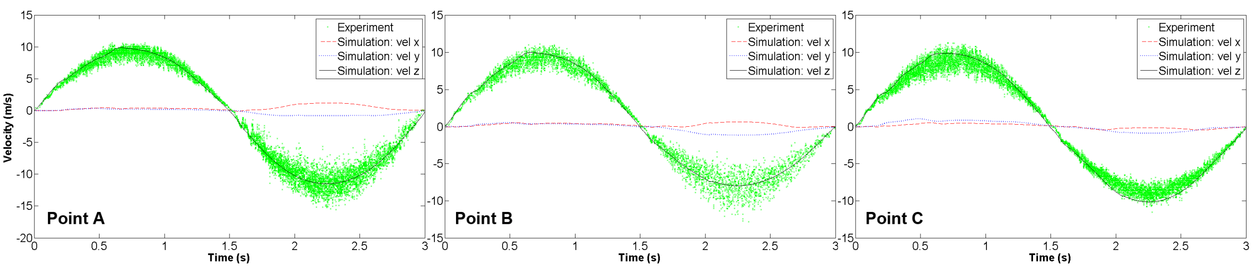

Fig. 4 Comparison of measured and calculated velocities for light activity

Velocities measured by P/DPA system and velocities in Z axis of local coordinate system calculated by CFD are compared. Comparison of the measured and calculated values was performed in MATLAB. Compared measurement data are not statistically evaluated. A comparison made in the three points show slightly higher velocity of the calculated values if compared with the measured data for all of three breathing regimes. Good agreement between experiment and calculation is seen for deep breathing and light activity during inspiration in time approx 0.25 s, where similar velocity change is apparent for both measured and calculated values. This change can be found in all measured points which mean that it has not influenced by surrounding geometry changes (laryngeal jet for point C or carina ridge of bifurcation for point A). Comparison also shows higher values of secondary velocities during expiration caused by air mixing in first bifurcation and higher turbulence in this area. This finding is significant for future research and it cannot be discovered without numerical simulation because P/DPA system gives us only one dimension of velocity in the investigated area.

6 Conclusion

Good agreement of numerical simulation and experimental data in axis of trachea allows us to complete the 1D velocity measurement in human upper airways, obtained by experiments provided by P/DPA, with 3D data of numerical calculations and give us more complex knowledge about flow characteristics in the investigated area.

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