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MEASUREMENT OF AIRFLOW IN TRACHEA USING PARTICLE IMAGE VELOCIMETRY AND LASER-DOPPLER ANEMOMETRY

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Abstract: *A lot of attention has been given to the study of airflow in human respiratory airways recently, because airflow characteristics greatly influence transport and deposition of the particles in human lungs. In this paper the aerodynamics occurring in upper part of human trachea is investigated. Laser optical measurements were performed in a semirealistic model of the upper airways, from mouth to 4th generation of branching. The model was attached downstream to a generator of oscillating flow, which was set to sinusoidal flow for resting conditions with mean Reynolds number Re = 1414. Flow characteristics were measured using laser optical methods, in particular Particle Image Velocimetry and Laser-Doppler Anemometry. We found that the flow in trachea was biased to the front wall due to the laryngeal jet. The flow became turbulent during high velocity phases of the sinusoidal flow and generated turbulence intensity was observed up to 20 %. These data can help to understand the complicated flow in trachea and its implications in particle deposition studies.*

Keywords: **Particle image velocimetry, Laser-Doppler anemometry, Model of human lungs, Flow measurement, Laryngeal jet.**

1. Introduction

Transport of particles in human lungs is greatly influenced by the patterns of the airflow, such as turbulence levels and vortices. Therefore investigation of airflow characteristics in human respiratory airways has attracted much attention in recent decades. Results of these studies play key role in toxicology or drug delivery. During inspiration the air flows through mouth to pharynx, where it turns rapidly and enters larynx through epiglottis.

The complex laryngeal anatomy heavily affects the air flow entering the trachea and creates a jet (Corcoran and Chigier, 2000). This so-called laryngeal jet forms eddies, reverse and turbulent flows, which leads to increased deposition in trachea region. Some researchers observed that the jet biased the flow towards the posterior wall of the trachea (Lin et al., 2007), however others found biased flow to the anterior wall (Zhang & Kleinstreuer, 2004). The behaviour of the jet varies depending on the geometry used (Kleinstreuer & Zhang, 2010).

Non-intrusive laser optical methods are efficient tools for analysis of airflow characteristics. Major drawback of these methods is the fact that the measurement area has to be optically accessible. Therefore, most of previous studies have used simplified models of the human lungs made of glass or silicone (Kim & Chung, 2009; Grosse et al., 2007). In addition the air was substituted by working fluid with the same refractive index as the model walls.

In this paper the experimental investigation of tracheal flows was carried out through a semirealistic upper airways model using both two-dimensional Particle Image Velocimetry (2D2C PIV) and one-dimensional Laser-Doppler Anemometry (1C LDA). By combination of these methods spatially and

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temporally resolved data of the flow were acquired. Air was used as working gas for preservation of real conditions.

2. Methods

2.1. Particle Image Velocimetry

Particle Image Velocimetry (PIV) was employed to acquire 2D-velocity flow fields in the simplified model of human upper airways displayed in Fig. 1b. The airways are modelled by thin-walled glass tubes, which facilitate measurement in various positions. The model includes respiratory airways from oral cavity to the 4^{th} generation of branching. Branch volumes, lengths and branching angles are preserved in comparison to human anatomy.

The experimental setup is displayed in Fig. 1a. The model (2) was attached to a generator of oscillating flow (1) comprising four pistons, two for inspiration and two for expiration phase, which were driven through cylinders by an electromotor (3). The electromotor was controlled by a computer (4) enabling simulation of different shapes of motion with proper amplitude and frequency. Sinusoidal cyclic flow for resting conditions (tidal volume of 0.5 l and period of 4 s) was chosen in this case. The flow was seeded with micrometric particles from incense sticks. Smoke inlets (5) were situated on both sides of the model to obtain homogenous distribution of particles during simulation of both inspiration and expiration.

Single camera PIV system was used to collect the data. A dual-head pulsed Nd:YAG laser (New Wave Gemini, 120 mJ per pulse, 532 nm) with laser beam collimator optics produced 0.5 mm thick light sheet (6). The light was brought to the investigated position in trachea through an articulated arm placed in posterior position. Images of the flow were captured by a TSI power View 4Mp CCD camera (7) equipped with a 60 mm focal lens and a circular polarizing filter. The camera axis was aligned perpendicularly to the light sheet, thus sagittal view of the trachea was acquired. The PIV system was triggered by TSI 610035 synchroniser. The measurements were carried out at five instants during the breathing cycle (phase 45°, 90°, 180°, 270° and 360°). A set of 50 images was obtained for each phase for phase averaging. The images were processed using Insight 3G software. Cross-correlation was performed to determine the displacement of the particles within a 50 % overlapping interrogation window 32×32 pixels in size, giving a spatial resolution of 19,7 μm/pixel.

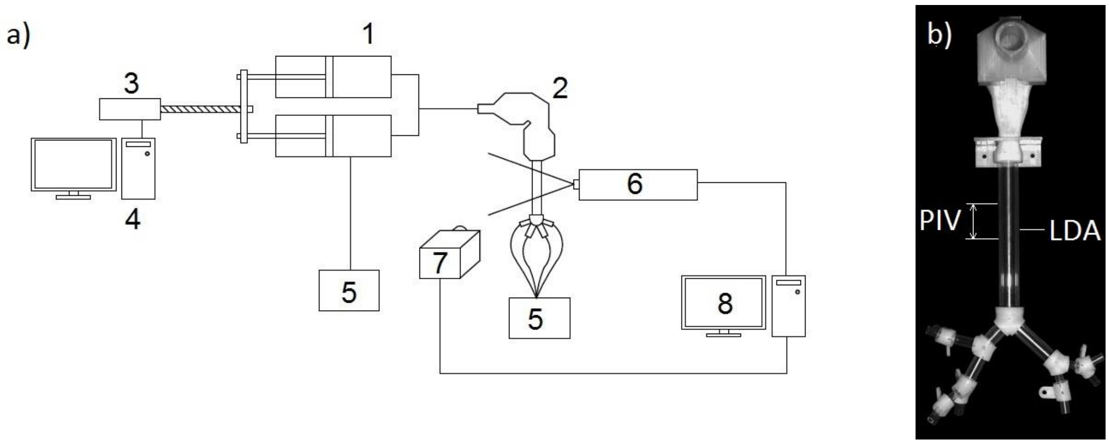

Fig. 1: a) Experimental setup; b) Model of human upper airways.

2.2. Laser-Doppler Anemometry

Point wise time-resolved measurement of flow velocity of particle-laden air in multiple points of the optically transparent model was provided under the cyclic breathing regimes using laser-Doppler anemometry (LDA). Dantec Dynamics Flow explorer 9065x0341 used BSA Flow software for measurement and analysis of the results. One pair of the crossing laser beams with wave length of 660 nm (power output: shifted beam 28 mW, un-shifted beam 33 mW) was used. The LDA worked in backscatter mode with the focal length of both the transmitter and receiver of 300 mm. Aerosol particles of di-2-ethylhexyl sebacate (DEHS) with 3 μm in diameter were produced by condensation monodisperse aerosol generator (CMAG TSI 3475), mixed in a static mixer with air and resulting dilute dispersed two-phase mixture was led to the lung model. The measurements were done in several points of one cross-section.

The LDA measured 1-component velocity and arrival time of individual aerosol particles. The velocity component normal to the corresponding cross-section of the tube in the airway model was traced. Temporally actual values of fluctuating velocity *v'*, were found by processing the velocity data samples in short time bins. Length of time window for the processing was set to a value significantly lower than the mean velocity change during the inspected time window (±15 ms in this case). Minimum number of particles in each time bin was set to 9. Dividing *v'* by spatially and temporally mean velocity in the point gives the axial turbulence intensity (TI). The plots (Fig. 3) are constructed as a result of several overlapped breathing cycles.

3. Results

PIV provides spatially resolved results of velocity fields. Measurements were executed in a region from 7 to 10 cm above the first bifurcation (Fig. 1b). Velocity field for different phases of sinusoidal flow and actual velocity profiles are displayed in Fig. 2. As mentioned earlier, the flow in trachea is influenced by laryngeal jet during inspiration. Under our kinematic conditions, the jet-flow was impinged to the anterior side of trachea. Fig. 2 illustrates higher velocities in the anterior side mainly for the 90° phase.

The velocity profile was rather parabolic for the phase 45°, thus the flow was laminar at this moment of the sinusoidal cycle. As the velocity and Reynolds number increased, the velocity profiles became flat, which indicated turbulent flow for the phases 90° and 270°. In addition, oscillatory flow character could have partly contributed to the flat profiles (Womersley number α = 2.7). Velocities during phases 180° and 360° were very low, as anticipated at the points of flow reversal.

As can be seen from the figures, the obtained data were not sufficiently good for PIV evaluation near the walls of the trachea. These blank regions were mainly created by reflections of the light. Moreover the amount of tracer particles was considerably smaller around the walls during high velocity phases.

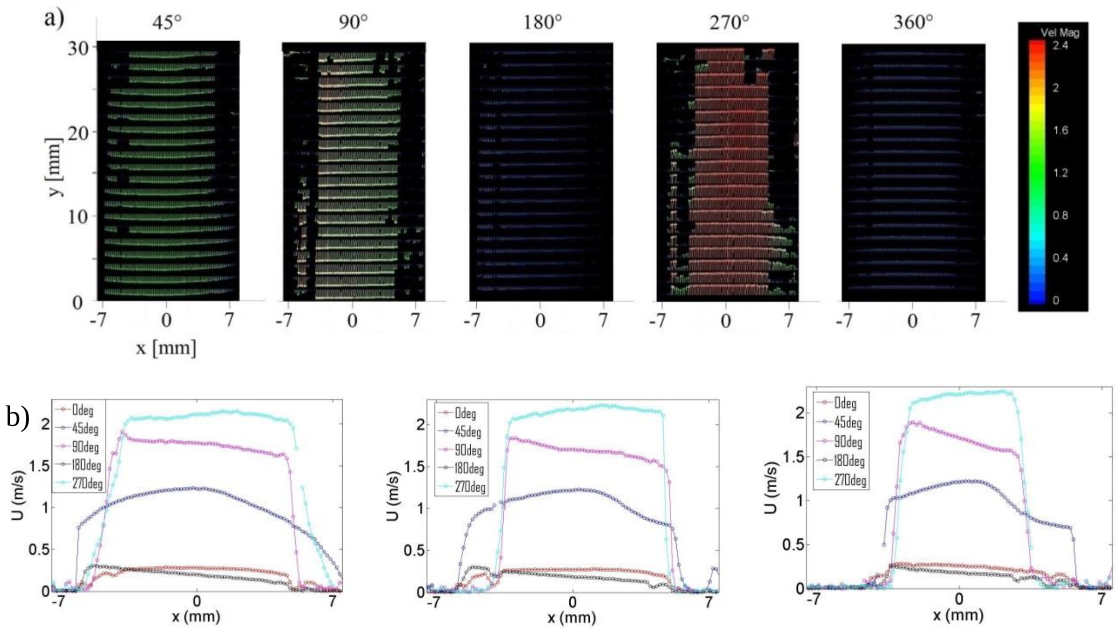

Fig. 2: a) Velocity fields for different phases of sinusoidal flow;
b) Velocity profiles in several cross-sections (y = 5; 15; 25 mm).

Illustrative results of the LDA measurements in two positions of the cross-section C (8 cm above the first bifurcation, Fig. 1b) are shown in Fig. 3. Time-resolved axial velocities of individual aerosol particles as well as averaged velocity profiles and TI for one full cycle are displayed. The mean velocity course generally resemble the sinusoidal character of the breathing cycle, but some fluctuations with time scale of tens of milliseconds are visible on the velocity and namely on the TI profiles. These large scale velocity fluctuations and jumps placed namely close to the velocity reversals suggest for vortical structures that attend the flow.

The inspiratory flow ($0 < t \leq 2$ s) is influenced by the laryngeal jet and, however the turbulence is already partially decayed due to long distance, it is still turbulent even for the resting conditions with mean Reynolds number Re = 1404. TI varies significantly during the flow. Inspiratory flow is influenced by the laryngeal jet (Lin et al., 2007), which generates turbulence with magnitude up to 20 % in both the points. It agrees with findings of others (Zhang and Kleinstreuer, 2004). Expiratory turbulence results from mixing of the streams from daughter branches. Its maximum is about 15 % for the centreline position and about 18 % for the R point. The expiratory part of the cycle for R point is more distorted from the sinusoidal shape.

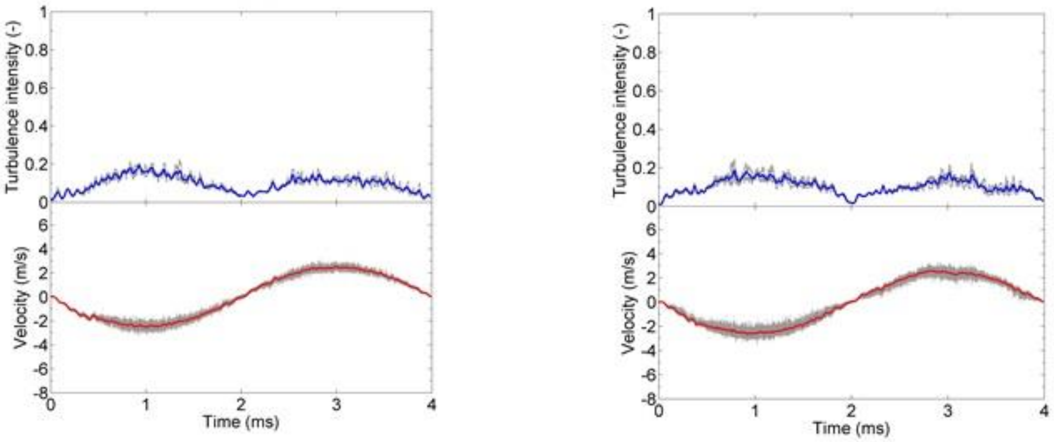

Fig. 3: Particle velocity during breathing cycle in cross-section 8 cm above the first bifurcation, in trachea centreline (left) and in position R (right), 4 overlapped cycles (right).

4. Conclusions

The spatially resolved velocity fields were obtained using PIV. The velocity profiles are asymmetrical during inspiration with higher velocities closer to the anterior side of the trachea. The observed velocity profiles were parabolic at low velocity phases, but they became flat at high velocity peaks indicating a transition from laminar to turbulent flow during the sinusoidal cycle. Moreover the effect of oscillation frequency was considerably low as expressed by Womersley number $\alpha = 2.7$.

This fact corresponds with the LDA results. The flow, as suggested by the TI plots, is relatively turbulent even for the resting conditions with mean Reynolds number Re = 1404. The time-resolved velocity curves acquired using LDA show small irregularities namely during the velocity reversals. These fluctuations and jumps are supposed to be caused by vortical structures that attend the flow.

The future work is planned to improve the quality of the PIV results and to mutually compare the methods.

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