Investigation on the Respiratory Airflow in Human Airway by PIV

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Received 6 October 2007
Revised 12 December 2008

Abstract: The creation of the accurate transparent flow passage is essential to analyze the flow inward a geometrically complex flow passage like human airway by PIV. We established the procedure to create a transparent box containing a model of the human airway for PIV measurements. A flow passage includes the whole human upper airway, nasal cavities, larynx, trachea, and 2 generations of bronchi. The phase averaged mean and RMS velocity distributions in sagittal and coronal planes are obtained for 7 phases in a respiratory period by tomographic PIV. Some physiologic conjectures are obtained. The main stream went through the backside of larynx and trachea in inspiration and the frontal side in expiration.

Keywords: Tomographic PIV, Biomedical flow, Human airway, CT, Physical Model

1. Introduction

The knowledge of airflow characteristics in total airway is essential to understand the physiological and pathological aspects of nasal breathing. Several studies have utilized physical models of the nasal cavities to understand the patterns of airflow (Scherer et al. 1989, Hess et al. 1992, Hopkins et al. 2000). Though the physical models become more sophisticated and PIV experiments on these models become popular recently (Kim and Son 2002, Doorly et al. 2006, Taylor et al. 2006), most investigators deal with models of airway only in part under constant flow condition. There have been some articles that have investigated the airflow of the mouth breathing both experimentally and numerically (Heeman et al. 2003, Liu et al. 2003, Johnstone et al. 2004.) The investigation on the airflow of nose breathing in a whole airway is very rare due to its geometric complexity. In this article, we investigate airflow in a whole airway including nasal cavities, larynx, trachea, and two generations of bronchi under periodic flow condition.

Creating the accurate transparent flow passage is essential to analyzing the flow inward a complex flow passage by PIV. Kim and Son (2002) improved the procedure to produce the better cavity model with high-resolution CT scan data and the surface rendering. Thin sliced CT data and meticulous refinement of model surface under the ENT doctor’s advice provided more sophisticated nasal cavity models. We applied this procedure to create models for abnormal nasal cavities with adenoid vegetation and asymmetry (Kim and Son 2004). Now, we extend this procedure to create a whole upper airway. This model is believed to be one of most anatomically correct one. The models of a nasal cavity and a whole airway are compared with the other models around world, which confirms the adequacy of our models. We design and construct the periodic pumping system to generate periodic flow simulating the physiological data of human respiration.

The phase averaged mean and RMS velocity distributions in sagittal and coronal planes were obtained for 7 phases in a respiratory cycle. The tomographic PIV technique is introduced to investigate complex flow structure in nasal cavity. Sixty sagittal sections with 1 mm in thickness are investigated by PIV measurements. The CBC PIV algorithm (Hart 2000) with window offset (64*64...
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to $32^*32$ is used for vector searching in PIV analysis (Kim 2001). The three dimensional reconstruction of velocity fields gives insights on flow characteristics of each part. Some physiologic conjectures are obtained. The main stream went through the backside of larynx and trachea in inspiration and the frontal side in expiration. There exist vortical motions in inspiration, but no prominent one in expiration.

Since we published many results on nasal airflows, presentations of results are focused on the airflow near larynx and trachea in this article. The paradigm established in this paper can be applied to many kinds of otorhinolaryngological and airway diseases and is believed to contribute to the diagnosis and treatment including surgical operation of airway diseases.

2. Experimental methodology

2.1 Creation of flow passage and working fluids

Creating an accurate transparent flow passage is essential to analyze the flow inward a complex flow passage by PIV. The key to producing a geometrically complex flow passage suitable for PIV is the recent availability of a rapid prototyping machine and water-soluble material for a negative model. Rapid prototyping is a well-accepted method for quickly generating replicate prototypes from computer files including CT scan data. A human airway is composed of nasal cavities, larynx, trachea, and 1-4 generation of bronchus, 5-(17-23) generations of bronchi, as shown in Fig.1a. The procedure of creating flow passages is summarized as follows: At first, a solid computer model for building the replicate model is created from coronal CT scan data (Somatom plus 4, Siemens Co., 0.6mm scan rate) of Korean adults (Fig.1b). Then, a replicate prototype of the nasal cavity, made of water-soluble cornstarch, is created by a RP machine (Z Co. MA. USA). This prototype is suspended in a rectangular Plexiglas box. Then, clear silicone is poured around the prototype carefully. After the silicone has been cured in an oven, the cornstarch prototype is removed with cold water. Finally, a rectangular box containing the form of the nasal cavity can be made. To remove the difference in the index of reflectance, the mixture of water and glycerin (52:48 in this case) is used as a working fluid. Due to the large amount of CT scan data (542 scan, 0.6mm increment) and the careful surface rendering, more sophisticated airway model can be made and used in this article. Irrelevant parts, such as sphenoid sinus, are removed to reduce the optical noise. While a 2X model of nasal cavity was made by the aforementioned procedure for the nasal airflow study, an actual size of upper airway is created in this article. For this model, the constant flow-rate assumption is less persuasive from the dynamic similarity condition (Chung et al. 2006). Fig.2 and 3 show existing nasal cavity and upper airway models. Comparing with anatomical figures, the adequacy of our model is prominent. For the upper airway model, it is believed to be one of most accurate model. (Private discussion in World Congress on Biomechanics at Munich, 2006)