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# A 4DCT imaging-based breathing lung model with relative hysteresis

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ABSTRACT

To reproduce realistic airway motion and airflow, the authors developed a deforming lung computational fluid dynamics (CFD) model based on four-dimensional (4D, space and time) dynamic computed tomography (CT) images. A total of 13 time points within controlled tidal volume respiration were used to account for realistic and irregular lung motion in human volunteers. Because of the irregular motion of 4DCT-based airways, we identified an optimal interpolation method for airway surface deformation during respiration, and implemented a computational solid mechanics-based moving mesh algorithm to produce smooth deforming airway mesh. In addition, we developed physiologically realistic airflow boundary conditions for both models based on multiple images and a single image. Furthermore, we examined simplified models based on one or two dynamic or static images. By comparing these simplified models with the model based on 13 dynamic images, we investigated the effects of relative hysteresis of lung structure with respect to lung volume, lung deformation, and imaging methods, i.e., dynamic vs. static scans, on CFD-predicted pressure drop. The effect of imaging method on pressure drop was 24 percentage points due to the differences in airflow distribution and airway geometry.



## 1. Introduction

Quantitative computed tomography (CT) has been used to obtain accurate structures of the airways and lobes of the lungs [8]. An image registration technique can link two static CT images to describe regional lung functions [31], and it has been utilized to characterize functional alterations due to lung diseases [1,2,4,7]. While two static images can provide linear lung deformation, three static images can reproduce non-linear lung deformation, but in the absence of lung hysteresis [30,10]. To better understand regional physiological lung function, we recently acquired four-dimensional (4D, space and time) dynamic CT images along with static images [9]. The study showed the relative hysteresis of anisotropic lung deformation with respect to lung air volume (simply "lung volume" hereafter), and demonstrated that regional ventilation derived from dynamic images is consistent with local air-volume change derived from two static images.

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While image registration can provide information on regional ventilation and lung deformation, computational fluid dynamics (CFD) models can provide information regarding gas flow, particle transport, and heat transfer in the human lung [13,17,28]. For example, CFD-based models can predict the location of particle deposition on the airway wall to investigate the regional differences associated with specific particulate matter, e.g., aerosolized pharmaceutical drugs and pollutants, to the human lung. It remains difficult to study these phenomena in detail using experimental methods in a subject-specific manner.

In most of previous CFD simulations for lungs, airway geometry was assumed to be rigid due in part to the complexity of geometric modeling and flow simulation methods, availability of data, and computational cost. However, in reality, lungs deform and thus, e.g., airway diameter and length vary during breathing. Furthermore, airway deformation could have a stronger influence on airflow in diseased lungs. For example, the variation of trachea diameter is larger in patients with acquired tracheobronchomalacia, resulting in airflow limitation during quiet breathing [14]. Therefore, CFD simulations with deforming airway geometry would provide more realistic results.

There are mainly two ways to model deforming lungs: fluid structure interaction (FSI) and imaging-based models. FSI models solve for both tissue deformation and airflow, but they require realistic tissue properties [27,29]. In contrast, imaging-based models require prescription of tissue deformation, but they are computationally less expensive than FSI models as they do not solve for tissue deformation [16,23,30]. For example, Mead-Hunter et al. [16] and Sera et al. [23] deformed their lung models using one image, prescribing the deformation based on the location of arbitrary points relative to a reference point. Yin et al. [30] used two and three static images to deform their lung models with a sinusoidal waveform, interpolating airway geometry as a function of time.

In order to reproduce lung hysteresis [15], one needs to use images at at least four time points: end expiration, during inspiration, end inspiration, and during expiration. In addition, static images provide quasi-static regional ventilation, which could result in, e.g., un-physiological pressure drop. 4D-dynamic images can be taken at four time points or more per breathing cycle, thus they can provide dynamic regional ventilation. While we proposed a CFD model using three static images [30], using dynamic images in a CFD model is not necessarily a simple extension of the previous model due to more irregular lung deformation. Therefore, the main objectives of this study are twofold. First, we aim to develop a CFD model for a deforming human lung using 4DCT images. Second, we investigate the effects of relative hysteresis of lung structure with respect to total lung air volume, airway deformation, and dynamic vs. static imaging methods on pressure drop along the central airways.

In this paper we present new methodologies that allow the application of a CFD model to 4DCT image data. Having established the 4DCT CFD procedure, we apply it to a previously acquired data set of a healthy human volunteer to demonstrate regional divergence of predictions in deforming and rigid airway models when using the full 4D data set vs. multiple combinations of limited time points and statically vs. dynamically acquired CT images.

## 2. Methods

We performed CFD simulations of airflow in deforming and rigid airway models based on 4D dynamic and static CT images. The overall 4DCT CFD procedure is illustrated in Fig. 1. The dynamic images were obtained at 13 time points (Fig. 1(a)). Deformations of airway surface meshes were obtained prior to CFD simulations by means of an image registration technique [31] and the constrained cubic-spline interpolation function [12] (Figs. 1(b)–(e)), whereas airway volume meshes were deformed during simulations using a computational-solid-mechanics (CSM)-based algorithm bounded by the surface meshes. As for airflow boundary conditions, the flow rates at the branches at the distal end of CT-resolved bronchial tree (simply "ending branches" hereafter) were determined in a physiologically realistic manner using an image registration technique and a volume-filling method [25,30] (Figs. 1(b)(c)(f)(g)). Using the above methods, we compared several airway models constructed with dynamic and static images to investigate the effects of relative hysteresis, airway deformation, and imaging method, i.e., dynamic vs. static scans, on the CFD solutions. Each step in Fig. 1 is described in more detail below. Specifically, Figs. 1(a)–(c) are described in the subsection 2.1, Figs. 1(d)(e) are described in the subsection 2.3, and Figs. 1(f)(g) are described in the subsection 2.4.

### *2.1. CT image acquisition*

In this study, we developed the numerical methods using 4D-dynamic and static CT lung images, acquired by Jahani et al. [9], of one of five healthy human subjects. A static image is obtained through conventional spiral scanning while a subject is holding his or her breath, whereas dynamic images are obtained through retrospective reconstruction of multiple point within the tidal volume range obtained from slow pitch spiral scanning during controlled tidal breathing [9]. Therefore, the geometric models based on static and dynamic images may reflect very slow respiratory rates (static acquisitions) and more physiologically meaningful (dynamic) rates, respectively. All subjects were studied in the supine body posture. As for the development of an empirical airflow boundary condition for the rigid airway model based on one static image, we used the data of all five subjects. The imaging protocols and subsequent image assessments here were approved by the Institutional Review Board and the Radiation Safety Committee of the University of Iowa.

The five subjects (Subjects 2–6 in [9]) consisted of two females and three males, their ages ranging from 23 to 58 years. A total of 13 volumetric lung images representing 13 time points within the respiratory cycle were reconstructed to capture