Clinical Biomechanics 50 (2017) 145–153

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Computational fluid dynamics evaluation of excessive dynamic airway collapse

Shahab Taherian[a,*], Hamid Rahai[a], Bernardo Gomez[a], Thomas Waddington[b], Farhad Mazdisnian[c]

[a] Center for Energy and Environmental Research and Services, California State University Long Beach, 1250 Bellflower Boulevard Long Beach, California 90840, USA
[b] Mount Nittany Medical Center, Pulmonary Division, 3901 South Atherton St. Suite 2, State College, PA 16801, USA
[c] Pulmonary Division, Long Beach Veterans Administration (LBVA) Hospital, 5901 E 7th St, Long Beach, CA 90822, USA

ARTICLE INFO

Keywords:
Excessive dynamic airway collapse
Computational fluid dynamics
Respiratory functional imaging
Simulation

ABSTRACT

Background: Excessive dynamic airway collapse, which is often caused by the collapse of the posterior membrane wall during exhalation, is often misdiagnosed with other diseases; stents can provide support for the collapsing airways. The standard pulmonary function tests do not necessarily show change in functional breathing condition for evaluation of these type of diseases.
Methods: Flow characteristics through a patient's airways with excessive dynamic airway collapse have been numerically investigated. A stent was placed to support the collapsing airway and to improve breathing conditions. Computed tomography images of the patient's pre- and post-stenting were used for generating 3-Dimensional models of the airways, and were imported into a computational fluid dynamics software for simulation of realistic air flow behavior. Unsteady simulations of the inspiratory phase and expiratory phase were performed with patient-specific boundary conditions for pre- and post-intervention cases to investigate the effect of stent placement on flow characteristic and possible improvements.
Findings: Results of post-stent condition show reduced pressure, velocity magnitude and wall shear stress during expiration. The variation in wall shear stress, velocity magnitude and pressure drop is negligible during inspiration.
Interpretation: Although Spirometry tests do not show significant improvements, computational fluid dynamics results show significant improvements in pre- and post-treatment results, suggesting improvement in breathing condition.

1. Introduction

Expiratory central airway collapse (ECAC) is the narrowing of the airways during expiration, which is divided into Tracheomalacia (TM)/Tracheobronchomalacia (TBM) and Excessive Dynamic Airway collapse (EDAC) (Murgu and Colt, 2013). Current methods of assessment of these diseases are challenging due to the similarity of symptoms to other diseases and conventional static medical imaging. Although dynamic imaging has proven to be effective in the diagnosis of these diseases, understanding air flow function and behavior is of great interest to researchers and clinicians for assessment and diagnosis.

Infections, inflammatory disorders, malignancy and extrinsic compression from adjacent structures can result in tracheal disorders; stenosis or an upper airway obstruction, is the manifestation of these diseases. Compared to lower airway obstructions, tracheal obstructions can be life threatening, since there are no collateral ventilations that can distribute the air to other airway branches (Al-Qadi et al., 2013).

The incidence of EDAC and TBM rely heavily on the narrowing airway lumen percentage criteria, historically by more than 50% and recently by more than 80% (Murgu and Colt, 2013) in lumen reduction, and it is reported to be between 4 and 22% of patients with chronic obstructive pulmonary disease (COPD) and/or asthma (Bruno and Mariotta, 2013; Dal Negro et al., 2013; Murgu and Colt, 2013).

Although EDAC is often mentioned interchangeably and incidentally with TBM, there are morphological and pathophysiological differences between these diseases. TM and TBM are characterized by weakness of the cartilaginous structure in the trachea and can extend to one or more primary bronchi, respectively; whereas EDAC is the collapse of the posterior membrane wall during exhalation or coughing, and it is unrelated to cartilage function and collapse (Al-Qadi et al., 2013; Murgu and Colt, 2013). TBM and EDAC can be classified into five domains: functional impairment, morphology, origin, length and

* Corresponding author.
E-mail addresses: shahab.taherian@csulb.edu (S. Taherian), hamid.rahai@csulb.edu (H. Rahai), bernardo.gomez@outlook.com (B. Gomez), thomas.waddington@mountnittany.org (T. Waddington), farhad.mazdisnian@va.gov (F. Mazdisnian).

http://dx.doi.org/10.1016/j.clinbiomech.2017.10.018
Received 6 February 2017; Accepted 25 October 2017

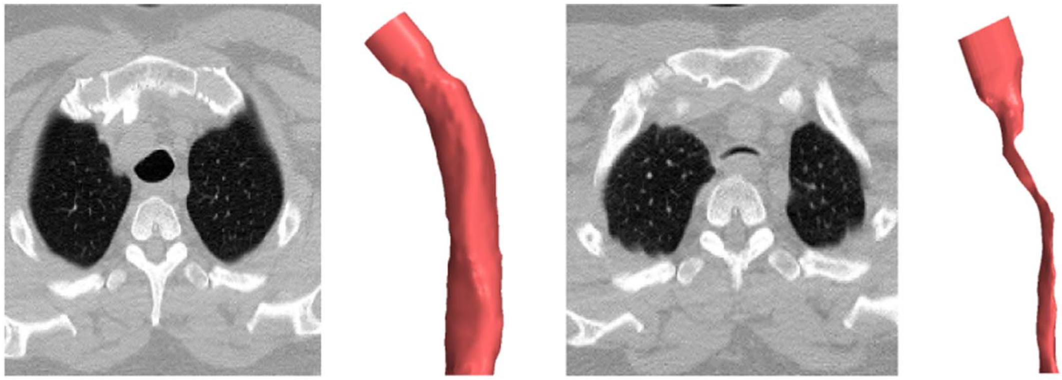

Fig. 1. CT-Images before stent placement at peaks of inspiration (left) and expiration (right) cycles, and their respective 3-D segment models of the trachea.

Table 1
Pulmonary function test (PFT) results of a patient diagnosed with EDAC before and after stenting. Although forced expiratory volume 1(FEV1) divided by forced vital capacity (FVC) does not indicate an obstruction (less than 70%) before intervention, the FEV1 increases (by more than 200 ml), as well as an increase in FEV1/FVC ratio is observed in post interventions. However, these values are neither significant nor sensitive to ECAC diseases.

Pre-stent spirometry		Ref	Pre	%Ref	Post-stent spirometry	Ref	Pre	%Ref
FVC	Liters	4.85	4.31	89	FVC	4.82	4.23	88
FEV1	Liters	3.76	3.10	82	FEV1	3.73	3.39	91
FEV1/FVC	%	78	72	93	FEV1/FVC	77	80	104

location abnormality, and severity of airway collapse (Dal Negro et al., 2013; Murgu and Colt, 2013). However, additional parameters, such as flow behavior, can significantly help with the assessment, pre-operative planning and post-therapy monitoring of these diseases.

Various diseases can be associated to ECAC. Physiological studies demonstrate that collapsed airways in EDAC patients might be the consequence of COPD, resulting from decreased elastic recoil, small airway inflammation and atrophy of elastic fiber, asthma, bronchiectasis and bronchiolitis due to small airway inflammation, and obesity due to positive pleural pressure (Murgu and Colt, 2013).

Different diagnosis modalities can be used for the diagnosis of TBM/EDAC, and can be categorized into invasive and non-invasive diagnosis. The gold standard for dynamic tracheal collapse visualization is by bronchoscopy, which is an invasive procedure. CT scans can be used as a non-invasive tool for diagnosis of ECAC; CT-scans provide additional information (on the vasculature, masses/tumors or parenchymal changes near the trachea) to understand the causes of ECAC (Murgu and Colt, 2013). However, the static inspiratory or expiratory phase cannot truly indicate the degree of airway collapse and thus making dynamic CT-scans a superior choice. Generally, CT-scans are used for pre- and post-operation (e.g. stent) assessment, to monitor possible complications such as mucus obstruction or choke point migration (Murgu and Colt, 2013).

Stents can provide support for the collapsing airways; metallic and silicon stents are used for these types of diseases, with the former being the primary choice due to fewer complications (Dal Negro et al., 2013; Murgu and Colt, 2013). As a foreign body, stents generally may cause disturbances in the clearance of mucosa, resulting in plugging with a tendency to initiate local infection sites (Zarogoulidis et al., 2015). In order to monitor the stent's possible adverse effects, a follow-up bronchoscopy or dynamic CT have been used (Murgu and Colt, 2013). However, the effect of location of stent placement on airflow has not systematically been considered in the pre-clinical setting.

For the past decade, there has been a large body of research covering Computational Fluid Dynamics (CFD) simulations of the airways, with small relevant sample discussed here. There have also been investigators who have focused on CFD and fluid-structural interactions (FSI) of airway obstructions, tracheal stenosis, and stent placements (Malvè et al., 2011a; Malvè et al., 2011b; Pirnar et al., 2015; Zhao et al., 2013). However, to our knowledge, there has not been a CFD investigation for airflow evaluation of EDAC and the effect of stent placement on its prognosis.

FSI simulation could be used to demonstrate the effects of the interactions of air with cartilaginous and muscle structure, but there are major challenges with this approach. The most prominent challenge is the patient specific local structural (trachea) property changes due to various types of diseases. The lack of accurate structural property of this disease makes the traditional FSI impractical.

Also, the majority of CT-based CFD and FSI simulations of the airways only consider the CT-based models of the inspiratory phase. However, in EDAC disease the reduction in the airway lumen and collapse of the trachea are during expiration phase; thus, making the simulations of only inspiratory phase models inaccurate. Here we use four sets of CT-Images. In order to understand the effect of stent placement on flow characteristics, inspiratory and expiratory CT images were used (Fig. 1) in both pre- and post-stenting for 3-Dimensional(3-D) model generation, as well as defining patient specific boundary conditions.

2. Three-dimensional models

CT-images provided by the Long Beach Veterans Administration (LBVA) Healthcare System were transferred to Mimics (Materialise) software for image segmentation and 3-D model generation. The models were then transferred to the STAR-CCM + (Siemens) software for CFD analyses. Four sets of CT-images were used in this study; pre- and post-intervention CT-based models of a patient diagnosed with EDAC were simulated during the inspiratory-expiratory cycle.

The branching airways below the trachea were not included in previous studies (Brouns et al., 2006; Chen et al., 2014; Malvè et al., 2011a; Mylavarapu et al., 2013; Zhang and Kleinstreuer, 2011), with few exceptions (Luo et al., 2007; Xi et al., 2008). In this study, branching sections up to 6–8 generations have been included. Although the main concentration in the trachea and upper airway analysis is the flow behavior in these regions, the upstream pressure could be affected if the lower generations are omitted. It is important to note that the larynx and oropharynx regions have shown to influence the flow behavior downstream in a healthy subject (Taherian et al., 2016). However, the high degree and length of collapse in this patient reduce the impact of upper regions in the trachea and lower generations. The authors are currently investigating these matters.

3. Computational fluid dynamics methods

The effect of EDAC on flow behavior in the trachea has been