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Numerical modeling of a human stented trachea under different stent designs☆

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ABSTRACT

Endotracheal stenting is a common treatment for tracheal disorders as stenosis, cronic cough or dispnoea episodes. However, medical treatment and surgery are still challenging due to the difficulties in overcoming potential prosthesis complications. In this work we analyze the response of the tracheal wall during breathing and coughing conditions under different stent implantations. A finite element model of a human trachea was developed and used to analyze tracheal deformability after prosthesis implantation under normal breathing and coughing using a fluid-structure interaction approach (FSI). The geometry of the trachea is obtained from computed tomography (CT) images of a healthy patient. A structured hexahedral-based grid for the tracheal wall and an unstructured tetrahedral-based mesh with coincident nodes for the fluid were used to perform the simulations with a finite element-based commercial software code. Tracheal wall is modeled as a fiber reinforced hyperelastic solid material in which the anisotropy due to the orientation of the fibers is taken into account. Deformations of the tracheal cartilage rings and of the muscle membrane, as well as the maximum principal stresses in the wall, are analyzed and compared with those of the healthy trachea in absence of prosthesis. The results showed that, the presence of the stent prevents tracheal muscle deflections especially during coughing. In addition, we proposed a methodology to evaluate, through numerical simulations, the predisposition of the stent to migrate.

1. Introduction

The trachea is a highly deformable duct which undergoes volume variation during normal breathing, coughing and sneezing. It is mainly composed by a number between 15 and 20 of cartilaginous rings, and a muscular membrane that runs longitudinally and posteriorly to the trachea. The main role of the tracheal cartilaginous structures is to maintain the windpipe open despite the inter-thoracic pressure during the respiratory movements [1]. Smooth muscle contraction and transmural pressure generate bending and tensile stresses in the cartilage and collapse it to regulate the air flow and modulate the diameter of the airway. A clear understanding of how this process is performed and how the implantation of a prosthesis affects the response of the trachea is therefore very important and challenging. Despite this importance, only few studies have analyzed the behaviour of the trachea under different ventilation conditions. This is especially relevant for instance in patients that have to be surgically treated. In particular, understanding of the breathing and coughing processes in the healthy trachea after prosthesis implantation is essential in order to design better adapted and maybe personalized prostheses.

Laryngeal and tracheal stents are solid or hollow absorbable or nonabsorbable tubes of various shapes, sizes, and materials whose mission is to prevent the trachea from collapsing. Although after prosthesis implantation, patients gain around 50% of their initial breathing capability, other problems such as coughing difficulties may take place, because of the increase in stiffness of the tracheal wall due to the presence of the prosthesis [2,3]. Other typical problems are stent migration, inflammatory granulation tissue formation, and obstruction secondary to the interference with mucociliary clearance [3]. In particular, silicone stents have a small inner diameter due to its thick wall, thus increasing the risk of mucous plugging [3]. For this reason, a better understanding of the healthy and pathological tracheal flow and of the distinct features of tracheobronchial stents through FSI analysis is necessary to improve clinical outcomes.

We could not find any previous numerical study on respiratory flow through stented tracheas. Most of the published works analyzed the airflow pattern using idealized or approximated airways geometries [4–7], while only a few were based on accurate airways geometries obtained from computerized tomography (CT) or magnetic resonance imaging (MRI) [8–14]. While all these studies do not take airway deformation into account [4,6,7,15–18], more recently, fluid solid

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