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Large Eddy Simulation of the pharyngeal airflow associated with Obstructive Sleep Apnea Syndrome at pre and post-surgical treatment

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ABSTRACT

Obstructive Sleep Apnea Syndrome (OSAS) is the most common sleep-disordered breathing medical condition and a potentially life-threatening affliction. Not all the surgical or non-surgical OSAS therapies are successful for each patient, also in part because the primary factors involved in the etiology of this disorder are not completely understood. Thus, there is a need for improving both diagnostic and treatment modalities associated with OSAS. A verified and validated (in terms of mean velocity and pressure fields) Large Eddy Simulation approach is used to characterize the abnormal pharyngeal airflow associated with severe OSAS and its interaction with the airway wall in a subject who underwent surgical treatment. The analysis of the unsteady flow at pre- and post-treatment is used to illustrate the airflow dynamics in the airway associated with OSAS and to reveal as well, the changes in the flow variables after the treatment. At pre-treatment, large airflow velocity and wall shear stress values were found at the obstruction site in all cases. Downstream of obstruction, flow separation generated flow recirculation regions and enhanced the turbulence production in the jet-like shear layers. The interaction between the generated vortical structures and the pharyngeal airway wall induced large fluctuations in the pressure forces acting on the pharyngeal wall. After the surgery, the flow field instabilities vanished and both airway resistance and wall shear stress values were significantly reduced.

1. Introduction

Obstructive Sleep Apnea Syndrome (OSAS) is a potentially life-threatening affliction (Partinen et al., 1988; Campos-Rodriguez et al., 2005) with up to 20 million affected people in the US alone (Young et al., 1993). It is the second most common sleep disorder after insomnia and the most common sleep-disordered breathing condition (Roth, 1995). OSAS results from repetitive partial or complete narrowing of the pharyngeal airway during sleep. Snoring and excessive daytime sleepiness are its two most common symptoms and studies have shown a progressive increase in the severity of the disease over time (Eckert and Malhotra, 2008).

Despite of the well known consequences, OSAS treatment remains unsatisfactory (Guilleminault et al., 2005; Schmidt-Nowara et al., 1995; Marti et al., 2002). The surgical procedures (uvulo-pharyngeal palatoplasty, mandibular advancement, adenotonsillectomy) are complex and invasive, while non-surgical options like continuous positive airway pressure, although effective, are not well tolerated by patients.

Quantitative and accurate non-intrusive methods are needed to facilitate a correct diagnosis, to identify the causes for which a patient has difficulties in breathing, and to target an optimal intervention strategy for OSAS. Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) have little clinical utility for quantifying the functional impact of an airway obstruction or the outcomes from a potential surgical intervention. They can offer information about the geometry of the respiratory tract, but cannot offer details about the effect of the anatomical characteristics on airflow or on airway resistance.

In order to improve therapeutic success rates, several investigators have proposed using computational modeling techniques to better understand the underlying biomechanics of obstruction. Such techniques employ medical imaging (CT or MRI) and Computational Fluid Dynamics (CFD) modeling to generate from imaging data a virtual airway model in which the airflow is simulated and flow variables of interest such as pressure, velocity, and wall shear stress (WSS) are extracted (Xu et al., 2006; Sung et al. 2006; Vos et al., 2007; Jeong et al., 2007, Mihaescu et al., 2008a; 2008b; De Backer et al., 2008). A major limitation with these models is the use of a steady-state flow formulation, usually Reynolds Averaged Navier–Stokes (RANS) with correspondent turbulence closures (Wilcox, 1993) that assumes a fully developed turbulent flow. RANS is robust and fast but it is hardly

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