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Effect of the velopharynx on intraluminal pressures in reconstructed pharynges derived from individuals with and without sleep apnea

Julien Cisonni[a,*], Anthony D. Lucey[a], Jennifer H. Walsh[b], Andrew J.C. King[a], Novak S.J. Elliott[a], David D. Sampson[c], Peter R. Eastwood[b,d], David R. Hillman[b]

[a] Fluid Dynamics Research Group, Department of Mechanical Engineering, Curtin University, Perth, WA 6845, Australia
[b] West Australian Sleep Disorders Research Institute, Department of Pulmonary Physiology and Sleep Medicine, Sir Charles Gairdner Hospital, Nedlands, WA 6009, Australia
[c] Optical+Biomedical Engineering Laboratory, School of Electrical, Electronic & Computer Engineering and Centre for Microscopy, Characterisation & Analysis, The University of Western Australia, Perth, WA 6009, Australia
[d] Centre for Sleep Science, School of Anatomy, Physiology and Human Biology, University of Western Australia, Nedlands, WA 6009, Australia

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ABSTRACT

The most collapsible part of the upper airway in the majority of individuals is the velopharynx which is the segment positioned behind the soft palate. As such it is an important morphological region for consideration in elucidating the pathogenesis of obstructive sleep apnea (OSA). This study compared steady flow properties during inspiration in the pharynges of nine male subjects with OSA and nine body-mass index (BMI)- and age-matched control male subjects without OSA. The k–ω *SST* turbulence model was used to simulate the flow field in subject-specific pharyngeal geometric models reconstructed from anatomical optical coherence tomography (aOCT) data. While analysis of the geometry of reconstructed pharynges revealed narrowing at velopharyngeal level in subjects with OSA, it was not possible to clearly distinguish them from subjects without OSA on the basis of pharyngeal size and shape alone. By contrast, flow simulations demonstrated that pressure fields within the narrowed airway segments were sensitive to small differences in geometry and could lead to significantly different intraluminal pressure characteristics between subjects. The ratio between velopharyngeal and total pharyngeal pressure drops emerged as a relevant flow-based criterion by which subjects with OSA could be differentiated from those without.

1. Introduction

Failure to maintain the patency of the upper airway during sleep characterizes obstructive sleep apnea (OSA), an extremely common and disabling disorder. This failure occurs as the result of a sleep-related loss of compensatory dilator muscle activity in individuals with anatomically predisposed airways. Many factors, including obesity and narrow skeletal confines, can contribute to this predisposition (Isono, 2012). These factors can act to both narrow the airway lumen (Rodenstein et al., 1990; Kim et al., 2008) and increase airway wall compliance (Schwab et al., 2003). The velopharyngeal airway appears to be particularly affected (Schwab et al., 1995; Arens et al., 2005). These anatomical characteristics combined with the aerodynamic forces created by inspiratory airflow through the complex airway geometry (Lucey et al., 2010) play an important role in the pathogenesis of OSA. Several studies have demonstrated the fluid–structure interaction mechanisms of upper airway collapse involved in OSA from idealized (Balint and Lucey, 2005; Chouly et al., 2008; Howell et al., 2009; Elliott et al., 2010) and realistic (Chouly et al., 2006; Zhu et al., 2012) geometric and tissue modeling.

Various imaging techniques can be used to obtain quantitative representations of an individual's airway geometry (De Backer et al., 2008). In general, previous imaging studies have shown a relationship between morphological features of the airway, such as upper airway length (Segal et al., 2008) or velopharyngeal size (Walsh et al., 2008), and the severity of OSA. However, it remains difficult to distinguish patients with OSA from healthy individuals using only geometric features of the airway (Vos et al., 2010). Further, it is generally accepted that a combination of parameters, including morphological data such as body-mass index (BMI), geometric data such as airway narrowness and flow characteristics such as airway resistance, is required to optimize OSA diagnosis and treatment evaluation (Vos et al., 2007). For example, pre- and post-treatment airway shapes, flow characteristics and apnea-hypopnea index (AHI) have been evaluated for mandibular advancement

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[*] Corresponding author. Tel.: +61 8 9266 7836.
E-mail address: julien.cisonni@gmx.com (J. Cisonni).

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devices (MAD) (Zhao et al., 2013), nasal surgery (Wang et al., 2012) and maxillomandibular advancement (MMA) surgery (Huynh et al., 2009; Mihaescu et al., 2011). These studies have shown a relationship between the reduction of AHI and the reduction of airway resistance but they have been limited to a small number of subjects. By contrast, Van Holsbeke et al. (2011) have used statistical analyses with a large number of subjects to identify the types of patients who would most benefit from mandibular repositioning (MR) to decrease airway resistance.

Direct numerical simulations (DNS) have revealed the very different flow patterns which can appear within the airway due to the complexity of the airway shape and the inter-subject variability (Nicolaou and Zaki, 2013). However, the use of large-eddy simulation (LES) or steady Reynolds-averaged Navier–Stokes (RANS) turbulence models can reduce the computational cost to simulate the flow within the airway and give accurate predictions of important flow features (Mihaescu et al., 2008; Cui and Gutheil, 2011). The validity of these models has been confirmed against *in vitro* measurements in reconstructed airways (Mylavarapu et al., 2009; Kim and Chung, 2009).

Anatomical observations have shown that the velopharynx tends to be narrower for patients with OSA (Walsh et al., 2008) and simulations have demonstrated that the narrowing of the velopharyngeal cross-section formed by the soft palate and posterior pharyngeal wall generates strong pressure gradients within this part of the pharynx and leads to an increase in airway resistance (Lucey et al., 2010). Flow simulations are thought to yield a stronger indicator of propensity to OSA than anatomical features because of the nonlinear relationship between geometric and flow characteristics within the pharynx (Nicolaou and Zaki, 2013). The main focus of the present study was therefore to determine the influence of velopharyngeal shape and size on the pressure drop across the pharynx and to evaluate the capacity of flow characteristics to identify individuals with and without OSA. Our hypothesis was that study of wakeful upper airway flow characteristics would more accurately distinguish such individuals than examination of airway dimensions alone.

2. Methods and materials

A comparison was made between the steady flow properties during inspiration in the reconstructed pharynges of nine subjects with OSA and nine control subjects without OSA.

2.1. Subjects

The subjects belonging to the OSA group (subjects A1–A9) were recruited from volunteer patients who had undergone a clinic-based polysomnogram that diagnosed or confirmed OSA (AHI >10). None had received any treatment for OSA or undergone upper airway surgery.

The subjects belonging to the control group (subjects C1–C9) were recruited from volunteers belonging to local service clubs matching the BMI and age values of the OSA group. None had a history of habitual snoring. They underwent a laboratory-based polysomnogram over a full night to confirm the absence of OSA.

The subjects of both groups were males and otherwise healthy. Subjects' age, BMI and AHI are reported in Table 1. The Human Research Ethics Committee at Sir Charles Gairdner Hospital approved the project and informed written consent was obtained from all participants.

2.2. Measurements

The airway geometry was measured with anatomical optical coherence tomography (aOCT), a minimally invasive endoscopic technique based on OCT with a near-infrared light, specifically adapted to map the anatomy of internal organs such as the airway (Armstrong et al., 2003, 2006; Leigh et al., 2008; Walsh et al., 2008). The system consisted of an optical probe placed inside a sealed, transparent catheter, with a 3 mm outer diameter. It operated by directing a light beam perpendicular to the catheter. The distance between the probe head and the air–tissue interface of the airway wall was determined from the reflected light using a low-coherence optical interferometer. The catheter was inserted via the nares to the level of the mid-esophagus (*cf.* Fig. 1) and taped to the external nares once in position. The probe rotated at 1.25 Hz to capture quantitative cross-sectional images of the upper airway.

The aOCT datasets used in this study were obtained from a pullback scan made while the subject was supine, relaxed and awake. The pullback scan involved retracting the optical probe within the catheter at a constant speed of 0.2 mm s^{-1} from the upper esophagus to the nasal cavity. During the scan, which took approximately 12 min to complete, subjects were instructed to breathe normally via the nose, to relax their tongue with the tip resting on the posterior surface of the upper incisors to ensure that a constant tongue position was maintained during scanning, and to indicate any swallowing. Simultaneously, rib cage and abdominal motion were continuously monitored by respiratory inductance pneumography.

For each subject, the aOCT dataset included more than 1000 images representing a quantitative cross-section of the airway in the plane orthogonal to the catheter. About one-third of the frames, corresponding to images acquired in the nasal cavity and in the esophagus, acquired during swallowing, or presenting lighting artifacts, were excluded from the analysis. Each frame was associated with a distance from the nares along the catheter and temporally aligned with the respiratory cycle (approximately 10 frames per period).

2.3. Airway geometry reconstruction

In order to build a 3-D model of the airway geometry during inspiration from each subject's aOCT dataset, between 10 and 20 cross-sectional images acquired at the end of inhalation (corresponding to a peak in the pneumography signal) were selected manually. These frames were chosen to obtain an accurate cross-sectional representation of important landmarks within the airway from the nasal septum to the upper esophageal sphincter.

The contour of the airway was estimated automatically from each selected frame using classical image processing techniques (noise attenuation, binarization, closing and opening, and thinning) and a spline interpolation of the extracted pixels in the local coordinates system (2-D plane perpendicular to the catheter).

During the aOCT measurements, the distance of the probe from the nares along the catheter was recorded but the exact location of the catheter within the airway was not known. In order to transform the local coordinates of the extracted airway contours in global 3-D coordinates, as shown in Fig. 2, a standardized probe path was estimated by assuming that the catheter remained rigid once taped in position at the external nares and held in place by contraction of esophageal muscle. The estimation of this generic probe path was based on other aOCT datasets for which the catheter location was obtained using a CT scan (Lucey et al., 2010), and defined with the following assumptions:

- The plane of the first extracted cross-section at the nasal end of the airway formed an angle of 75° with the $x-z$ plane.
- The plane of the last extracted cross-section at the esophageal end of the airway was parallel to the $x-z$ plane.
- The angle that formed the plane of the other extracted cross-sections with the $x-z$ plane decreased quadratically as a function of the distance of the probe from the nares along the catheter, between the first and the last cross-sections.
- The catheter was fixed in the z-direction.

Preliminary analyses showed the weak impact of the probe path estimation on the main flow quantities of interest, which varied less than 5% when the assumptions were changed within the limits of realistic geometric configurations.

The wall of the pharynx between the nasal septum and the esophageal sphincter was obtained with a cubic spline interpolation of the surface from the extracted cross-sectional contours in the global coordinate system. The barycenters of the interpolated cross-sections formed the airway centerline that was used to estimate the length of the pharynx L_P and to analyze the profiles of the flow properties along the pharynx.

2.4. Airflow simulation

Flow-field computations were carried out assuming a quasi-static flow in the pharynx since during quiet breathing, the airflow timescale is much shorter than that of the breathing cycle. Therefore, a static pressure-driven flow during inspiration was simulated for all subjects. These simulations were made using OpenFOAM software (Open CFD Ltd, 2011) with a finite-volume discretization of the steady RANS equations. The k–ω shear–stress transport (SST) turbulence model was used to solve the equations with the SIMPLE algorithm. Mihaescu et al. (2008) have suggested that an unsteady LES approach should be preferred to compute the flow-field within the airway in order to obtain more accurate predictions of important flow features such as flow separation. However, the k–ω SST model was chosen in this study not only because the assumption of a quasi-steady flow was made but also because this model is appropriate to flow with curvature and adverse pressure gradients (Wilcox, 1993), and has been shown to be a good