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Computational fluid dynamics for the assessment of upper airway response to oral appliance treatment in obstructive sleep apnea

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ABSTRACT

Mandibular advancement splints (MAS), which protrude the lower jaw during sleep, are recognized as an effective treatment for obstructive sleep apnea (OSA) through their action of enlarging the airway space and preventing upper airway collapse. However a clinical challenge remains in preselecting patients who will respond to this form of therapy. We aimed to use computational fluid dynamics (CFD) in conjunction with patient upper airway scans to understand the upper airway response to treatment. Seven OSA patients were selected based on their varied treatment response (assessed by the apnea–hypopnoea index (AHI) on overnight polysomnography). Anatomically-accurate upper airway computational models were reconstructed from magnetic resonance images with and without MAS. CFD simulations of airflow were performed at the maximum flow rate during inspiration. A physical airway model of one patient was fabricated and the CFD method was validated against the pressure profile on the physical model. The CFD analysis clearly demonstrated effects of MAS treatment on the patient's UA airflow patterns. The CFD results indicated the lowest pressure often occurs close to the soft palate and the base of the tongue. Percentage change in the square root of airway pressure gradient with MAS ($\Delta\sqrt{\Delta P_{Max}}\%$) was found to have the strongest relationship with treatment response (ΔAHI%) in correlation analysis ($r=0.976$, $p=0.000167$). Changes in upper airway geometry alone did not significantly correlate with treatment response. We provide further support of CFD as a potential tool for prediction of treatment outcome with MAS in OSA patients without requiring patient specific flow rates.

1. Introduction

Obstructive sleep apnea (OSA) is a common disorder characterized by repetitive episodes of complete (apnea) or partial (hypopnea) collapse of the upper airway during sleep, resulting in sleep disturbance and oxygen desaturation (American Academy of Sleep Medicine Task Force, 1999). OSA severity is defined by the apnea–hypopnea index (AHI), the total number of apneas and hypopnoeas per hour of sleep (Ferguson et al., 2006). OSA sequelae include excessive day time sleepiness, cardiovascular and cerebral vascular diseases (Roux et al., 2000).

Standard treatment is continuous positive airway pressure (CPAP) applied via a mask interface during sleep, which pneumatically splints the upper airway, preventing collapse. An alternative approach is mandibular advancement splint (MAS) treatment (Cistulli et al., 2004), which uses custom-made dental devices that hold the lower jaw in a protruded position. MAS stiffens upper airway tissues and reduces airway collapse, likely mediated through an increase in pharyngeal area predominantly in the lateral dimension (Ng et al., 2003; Chan et al., 2007).

MAS treatment is often preferred by patients due to its simplicity of use and portability, which often leads to better treatment adherence (Ng et al., 2003). While 60–70% of patients achieve clinical benefit, a complete treatment success (AHI < 5 after treatment) is only achieved in approximately 35–40% (Chan et al., 2007). Therefore treatment responses vary and pre-identifying which patients will respond to MAS therapy is currently not possible. Particular characteristics of OSA patients, OSA severity, obesity and craniofacial structure, have been associated with MAS treatment outcome, however such predictors have not been conclusively validated (Ferguson et al., 2006). Prediction of individual treatment outcome remains an elusive goal due to incomplete understanding of the mechanisms of MAS treatment (De Backer et al., 2007).

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Recently computational technologies and biomechanical theories have been applied to study upper airway mechanics in OSA. Computational fluid dynamics (CFD) has been used to model the upper airway (UA) flow field, originally based on simplified airway models (Martonen et al., 2002) but progressing to use of patient specific geometrical characteristics obtained from medical imaging, hence providing a more accurate assessment of airflow characteristics (Collins et al., 2007). CFD has now been utilized to assess the effects of OSA treatment interventions that alter upper airway anatomical structure. For example CFD analysis has been combined with upper airway geometries obtained before and after pharyngeal surgeries to determine the effects on parameters such as pressure drop and flow resistance (Xu et al., 2006; Mihaescu et al., 2011). Similarly CFD has been proposed as a tool to determine treatment response to MAS therapy using patient-specific airway geometries obtained from CT scans without and with MAS (De Backer et al., 2007). This study found a strong correlation between change in airway resistance with MAS using CFD and change in AHI from sleep study data. Increased pharyngeal volumes with MAS corresponded with a decrease in flow resistance, although the calculated resistance parameter was more closely associated with treatment outcome.

CFD is therefore an attractive method to model likely treatment outcome with MAS in patient-specific airway geometry before implementation of the device. In this original work (De Backer et al., 2007), the upper airway response to MAS therapy was modeled using patient-specific flow rates and pressures obtained during split-night sleep studies without and with the device. Although this is likely to provide greater model accuracy, obtaining such patient-specific boundary conditions by intensive overnight monitoring is likely to limit the clinical applicaction of this type of prediction strategy.

We wish to expand on this original concept study by using pharyngeal airway models from patient scans without and with MAS and generalized UA flow and pressure profiles to determine if a relationship with treatment outcome was still evident. This would greatly increase the viability of prediction based on computational methods. Additionally our airway models allowed us to look at the internal pressure forces that may contribute to upper airway collapse. We provide exciting evidence of the possibility of MAS treatment outcome prediction based on patient-specific static geometries alone and have furthermore validated our experimental findings using a physical model. Our results indicate a more reliable, but relatively simplified upper airway model for understanding MAS treatment outcome and provides encouragement of the possibility of a CFD approach applicable to clinical practice.

2. Methods and materials

2.1. Patients, MAS device and imaging

Seven OSA patients with a range of treatment response to MAS were selected from a larger imaging study of upper airway structure with MAS (Chan et al., 2010). Patient characteristics are shown in Table 1. Written informed consent was acquired from all patients. All patients used commercially available, customized two-piece MASs (Fig. 1, SomnoDentMAS; SomnoMed Ltd, Crows Nest, Australia) (Mehta et al., 2001).

Table 1
General characteristics of the seven patients in this study. (WO=without MAS, W=with MAS).

Patient	Age	BMI	AHI (WO)	AHI (W)
Responder 1	52	29.41	41.5	2.1
Responder 2	24	34.68	22	0
Responder 3	43	26.73	14.2	4.1
Partial-responder	31	24.26	28.4	13.9
Non-responder	49	36.65	29.2	23.6
Failure 1	65	25.1	19.5	25
Failure 2	57	28.34	16.0	31.7

Imaging was undertaken without and with MAS after an acclimatization period (6–8 weeks) during which the device was titrated to the patient's maximal comfortable limit. UA magnetic resonance imaging (MRI) was performed using a Philips INTERA 1.5T scanner (Philip Electronics, Netherlands) with the patient awake and in the supine position as previously described (Chan et al., 2010). Normal nasal breathing was requested with standardised head, tongue and jaw position. Axial image slices from the nasopharynx to the vocal cords were obtained for image post processing (50 slices, 3 mm thickness, 224×512 matrix, FOV 250 mm) (Chan et al., 2010).

Treatment response was determined by overnight polysomnography with MAS after the titration period. Four different types of treatment responses were defined by change from baseline polysomnography: "Responder" (post-treatment AHI $<$ 5/hr or no OSA), "Partial-responder" ($\geq$50% AHI reduction from baseline but AHI $>$ 5/hr), "Non-responder" ($<$50% AHI reduction) and "Failure" (post-treatment AHI increase). Patients were specifically selected to reflect the full spectrum of treatment outcome.

2.2. Upper airway mesh generation

The upper airway was segmented on axial image slices between the hard palate and the vocal folds (Amira 5, Visage Imaging, United States) (Fig. 2). The segmentation of the airway was used to create a surface model. This surface model was smoothed by shifting the vertices according to the average position of the neighboring vertices, preserving the airway structure. The UA surface model was exported as STL format into ANSYS ICEM CFD (ANSYS 13.0) to generate discrete volume cells. An unstructured tetrahedral volume mesh was generated in the airway surface model. Along the wall boundary, 5 layers of inflation grids were placed to accurately capture the boundary viscous layer (Fig. 3).

A mesh convergence study was performed on models of different grid scales (Fig. 4). The 1.3 million-mesh size (maximum grid edge length 0.5 mm) was chosen because it had acceptable accuracy but saved over 30% computational time compared to those with more elements.

2.3. Numerical modeling

The fluid governning equations were solved in ANSYS CFX 13.1 (ANSYS, United States). Considering the low Mach number of the UA airflow ($<$0.05) during inhalation, the flow was modeled as incompressible and Newtonian. The Reynolds number (*Re*) for the UA was estimated to range from 426 to 2834 meaning the flow is either laminar or transitional. The standard shear stress transport (SST) k–ω model was selected to model the flow turbulence. By comparing to the physical experimental result, our preliminary sensitivity study of applying different turbulence models proved the appropriateness of the SST k–ω model in solving the complex UA flow. It is in agreement with other studies that indicate that the SST k–ω model has advantages in solving complex transional flow (Menter, 2009) including the

Fig. 1. Custom-made two-piece MAS (SomnoDentMAS; SomnoMed Ltd, Crows Nest, Australia). The device used in the study resembles the one pictured with the exception of a modification of the metal screw advancement mechanism which was replaced with an acrylic advancement mechanism to allow the device to be worn during MR imaging. The design features and efficacy of this appliance have been previously published.