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Journal of Biomechanics 40 (2007) 3708–3714

JOURNAL OF BIOMECHANICS

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Functional imaging using computational fluid dynamics to predict treatment success of mandibular advancement devices in sleep-disordered breathing

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Accepted 19 June 2007

Abstract

Mandibular advancement devices (MADs) have emerged as a popular alternative for the treatment of sleep-disordered breathing. These devices bring the mandibula forward in order to increase upper airway (UA) volume and prevent total UA collapse during sleep. However, the precise mechanism of action appears to be quite complex and is not yet completely understood; this might explain interindividual variation in treatment success. We examined whether an UA model, that combines imaging techniques and computational fluid dynamics (CFD), allows for a prediction of the treatment outcome with MADs. Ten patients that were treated with a custom-made mandibular advancement device (MAD), underwent split-night polysomnography. The morning after the sleep study, a low radiation dose CT scan was scheduled with and without the MAD. The CT examinations allowed for a comparison between the change in UA volume and the anatomical characteristics through the conversion to three-dimensional computer models. Furthermore, the change in UA resistance could be calculated through flow simulations with CFD. Boundary conditions for the model such as mass flow rate and pressure distributions were obtained during the split-night polysomnography. Therefore, the flow modeling was based on a *patient specific* geometry and *patient specific* boundary conditions. The results indicated that a decrease in UA resistance and an increase in UA volume correlate with both a clinical and an objective improvement. The results of this pilot study suggest that the outcome of MAD treatment can be predicted using the described UA model.

Keywords: Imaging; Oral appliances; Sleep apnea; Snoring; Upper airway; Computational fluid dynamics

1. Introduction

The awareness of the potentially serious consequences of sleep related breathing disorders (SBD) such as obstructive sleep apnea hypopnea syndrome (OSAHS) is increasing. OSAHS is characterized by recurrent episodes of partial or complete collapse of the upper airway. This may lead to a fragmentation of the sleep pattern, a decrease in oxygen saturation and a partial pressure rise of CO_2 in the blood. The arousals and the nocturnal hypoxemia can cause excessive daytime sleepiness, loss of concentration, hypertension and atherosclerosis. In some cases, the pronounced presence of OSAHS may lead to stroke and even heart failure, resulting in an increased prevalence of cardiovascular morbidity and mortality (De Backer, 2006; American Academy of Sleep Medicine Task Force, 1999). Nowadays,

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0021-9290/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2007.06.022

the golden standard to assess the severity of sleep apnea is the apnea–hypopnea index (AHI). This index presents the number of UA narrowings and closures per hour. An AHI above 5 events h^{-1} in combination with complaints is regarded as an OSAHS.

Mandibular advancement devices (MADs), which are worn intra-orally at night to advance the lower jaw, have emerged as a non-invasive treatment for SBD (Marklund et al., 2004; Lim et al., 2006; Vanderveken et al., 2004). There is evidence that MADs can significantly reduce the collapsibility of the upper airway (UA) during sleep (Kato et al., 2000; Ng et al., 2003; Huang et al., 2005). The widening of the pharyngeal cross-sectional area (CSA) as induced by MADs can occur at the level of velo-, oro- and/or hypopharynx (Ryan et al., 1999; Kato et al., 2000; Tsuiki et al., 2004, 2005). Both the reduction in pharyngeal collapsibility and the widening of CSA, caused by MADs, have been reported to be dose-dependent (Kato et al., 2000; Tsuiki et al., 2005). However, in recent studies that compare different degrees of mandibular advancement, a more pronounced mandibular advancement did not lead to a greater improvement compared to less advancement for patients with mild to moderate OSAHS (Tegelberg et al., 2003; Walker-Engstrom et al., 2003).

MAD therapy may be a first line treatment in snorers without (primary) or with (non-apneic) excessive daytime sleepiness and in patients with mild to moderate OSAHS (Kushida et al., 2006; Ferguson et al., 2006; Hoekema et al., 2004). Treatment with MADs may also be considered in subjects with OSAHS who do not tolerate or comply with continuous positive airway pressure (CPAP) or as a temporary alternative (Lim et al., 2006; Smith and Stradling, 2002). Although promising, success rate with MADs is limited, and a high interindividual variability has been noted (Marklund, 2006a). Therefore, it would be worthwhile to have a tool to distinguish responders from non-responders. However, the data in the literature on predictability of treatment outcome with MADs are not conclusive and more research is needed to develop a adequate prediction method (Cistulli and Gotsopoulos, 2004; Cistulli et al., 2004). Recently, we have developed an UA model based on the principles of computational fluid dynamics (CFD) to develop an adequate prediction tool for interventions in the UA. (Vos et al., 2007). Computed tomography (CT) data are transformed into computational models and analyzed through CFD. In this paper, results of a pilot study using this UA model for the assessment of treatment success with MAD in SBD are discussed.

2. Material and methods

2.1. Patient data and mandibular advancement device

For this study 10 adult patients with heavy snoring and an apnea–hypopnea index (AHI) $<40\,h^{-1}$ on standard polysomnography (PSG) were selected. All of these patients were treated with a custom-made MAD. The custom-made MAD used in this study (Fig. 1) was fabricated by a dental technician based on individually made plaster casts of the teeth and a bite registration taken by our dentist; the MAD was constructed at the dental laboratory of the Umeå University, Sweden (Marklund et al., 1998, 2004; Marklund, 2006b). The study was performed according to institutional guidelines and informed consent was obtained for all patients.

2.2. Polysomnographic study

All patients underwent three sleep studies. The first diagnostic PSG confirmed an AHI below $40\,h^{-1}$. After a 4-month treatment period a similar standard PSG was performed with the MAD to determine treatment efficacy. Standard full-night PSG (Medilog SAC, Oxford Instruments, Oxon, UK) was performed. Finally, patients were invited for a split-night sleep study with and without the MAD. These split-night studies were performed using the Alice III system (Healthdyne Technologies, Marietta, GA, USA) and included standard PSG. Airflow was detected by a Fleisch No. 1 pneumotachograph. Continuous monitoring of respiratory effort was performed using the esophageal sensor of a multi-sensor UA catheter as previously described (Boudewyns et al., 2001; Vanderveken et al., 2005). Sleep recordings were scored manually in a standard fashion (American Academy of Sleep Medicine Task Force, 1999; Levy et al., 2006).

2.3. Computational domain and grid

The morning after the split-night PSG, two CT scans (Siemens Sensation 16 with a slice thickness of 0.5 mm) were performed with and without MAD. The scanning area started at the nasopharynx and extended down to the larynx. Based on these CT images the maxilla, mandibula and UA could be reconstructed into three-dimensional (3D) computer-aided design (CAD) models. We used Mimics® software (Materialise, Leuven, Belgium) for the construction of 3D models based on Hounsfield units (HU). In order to reconstruct 3D images based on

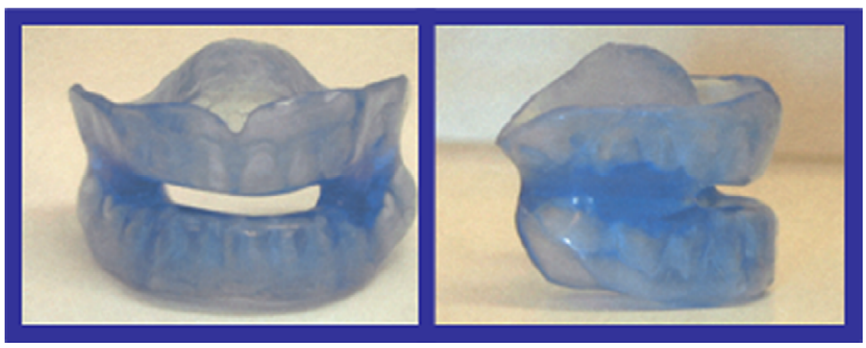

Fig. 1. Custom-made mandibular advancement device.