ASSESSING THE EFFICIENCY OF A MANDIBULAR ADVANCEMENT DEVICE TO TREAT OBSTRUCTIVE SLEEP APNEA USING COMPUTATIONAL FLUID DYNAMICS

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Abstract. *Obstructive Sleep Apnea (OSA) is a condition in which the patient repeatedly stops breathing during sleep due to the collapse of the upper airway. The upper airway collapse is caused by a relaxation of the upper airway muscles, combined with a decrease in intraluminal pressure and hence an increase in external pressure from the surrounding tissue. A possible treatment that is becoming more and more popular, due to its reversibility, is the oral intervention like a Mandibular Advancement Device. This device brings the mandibula forward in order to increase the upper airway volume and prevent total upper airway collapse during sleep. The patient only uses the device during the night. However the efficiency of the MAD can vary significantly from patient to patient. The use of Computational Fluid Dynamics allows for a prediction of the outcome of a treatment with an MAD. This makes it possible to compare upper airway volume and to determine the upper airway resistance (UAR) through finite volume flow simulations for both cases. Boundary conditions for the model are obtained from the patient during a sleep study. Therefore the flow modelling is based on patient specific geometry and patient specific boundary conditions. A mesh dependency and turbulence dependency study was performed. Whenever the simulations showed a decrease in upper airway resistance, also a clinical improvement was observed. Clinical improvements are measured by looking at the apnea-hypopnea index (AHI) which indicates the number of events (upper airway closures or near closures) per hour and the snoring index quantifying the degree of snoring. In conclusion, one can say that the combination of advanced imaging and functional analysis shows a large potential for future medical treatments.*

1 INTRODUCTION

Obstructive Sleep Apnea Syndrome (OSAS) is a sleep related breathing disorder characterized by repeated collapse of the upper airway. The closure of the upper airway causes the patient to stop breathing. This leads to oxygen desaturation, followed by an awakening of the patient. The result of having OSAS is sleep fragmentation. OSAS can be considered as a potentially very dangerous disease with possible severe consequences such as hypertension, atherosclerosis or stroke and even heart failure[1]. Symptoms of OSAS include amongst others daytime sleepiness, morning headaches and snoring.

In OSAS the airway collapses at the end of the expiration[2]. This is caused by an increased pressure of the surrounding tissue on the airway due to relaxation of the muscles and a decrease in intraluminal pressure at the end of the expiration. Several treatments exist for reducing or eliminating the effects of OSAS, the most effective one is Continuous Positive Airway Pressure (CPAP). Patients using CPAP, sleep with a mask that raises the intraluminal pressure in order to prevent airway collapse. Although efficient, CPAP is not always tolerated well by the patients due to the relatively high discomfort of sleeping with a mask. Therefore other treatments are used such as uvulopalatopharyngoplasty (UPPP) where parts of the upper airway are removed surgically to increase upper airway volume. The success rate of this kind of treatment does however vary quite substantially. An alternative that has become more and more popular due to its reversibility is the oral device such as the Mandibular Advancement Device (MAD). The MAD consists of a mouth piece that is used only during the night. It brings the lower jaw or mandibula forward, thereby increasing the upper airway volume.

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Figure 1 Marklund Mandibular Advancement Device

Figure 1 presents such a MAD as developed by Marklund[3]. The success rate of the MAD can be estimated between 55% and 65%. The aim of the current study is to see whether the efficiency of the MAD treatment can be correlated with anatomical characteristics and Computational Fluid Dynamics (CFD) calculations based on advanced imaging techniques. This correlation can be used to predict the outcome of the treatment in advance thereby increasing the success rate of the technique and at the same time optimizing patient care and reducing cost. Section 2 describes the methods that were used in this study. Section 3 presents the findings. Further discussion of these findings can be found in section 4 and finally section 5 formulates the conclusions.

2 METHODS USED IN THE STUDY

The methods used in this research project consist of the actual functional imaging and the clinical setting to validate the results of the functional imaging. For this project, 8 patients in total (7 male /1 female) were studied. All the patients were diagnosed with a mild to moderate form of sleep apnea and/or symptomatic snoring. All patients underwent a split night polysomnography. Polysomnography is a diagnostic test during which a number of physiologic variables are measured and recorded during sleep[4]. For this study the flow was measured using a pneumotach and the intraluminal pressures were measured using a multi-sensor pressure catheter during the night. The flow measurements allowed for an assessment of the number of apneas, the location of collapse could be determined using a multi sensor catheter. The first half of the night the patient slept without MAD, halfway during the night the patient was asked to use the MAD (split night approach). This test allowed for a clinical assessment of the efficiency of the MAD.

The morning after the split night, two Computed Tomography (CT) scans were taken; one with and one without the MAD.

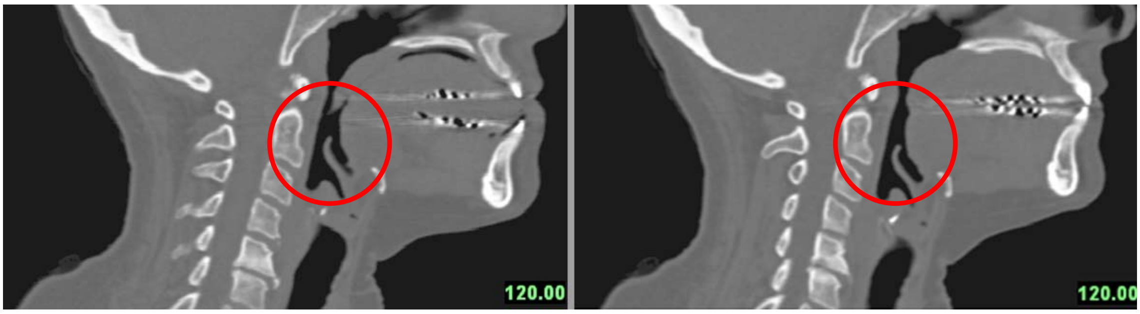

Figure 2 CT scan taken with (left) and without (right) MAD

Figure 2 illustrates the CT scans of a patient taken the morning after the split night. Based on these CT scans, three dimensional reconstructions can be made of the interesting parts. For this project one is mainly interested in the upper airway volume, the mandibula and maxilla. The reconstruction in based on the Hounsfield Units (HU) in the CT scans. These are a measure for the electron density of the tissue. The parts under consideration are grouped into masks that are converted into three dimensional Computer Aided Design (CAD) models.

Once the masks were defined accurately the three dimensional models could be constructed. Figure 3 presents the CAD models of the mandibula, maxilla and upper airway from a patient suffering from sleep apnea reconstructed based on the HU in the masks. On the left the patient is depicted without the MAD, the right image shows the effect of the MAD on the mandibular position and the upper airway volume.

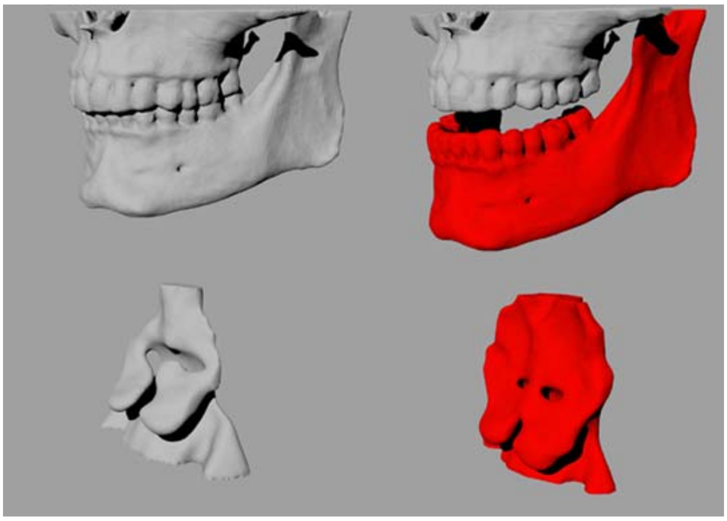

Figure 3 Three dimensional reconstruction of mandibula, maxilla (upper part) and reconstructed upper airway (lower part) for patient suffering from sleep apnea

Now that the upper airway volume has been converted into a three dimensional image, it can be used to analyse the flow behaviour inside the airway using Computational Fluid Dynamics (CFD) for both cases. CFD is a method that allows for a mathematical description of flow in a domain based on pre-defined boundary conditions[5]. To this end the Navier Stokes equations are solved numerically. This means that these equations are solved in discrete volume elements, also referred to as a computational grid. The results of a CFD calculation is that the local flow characteristics are known in every computational cell. The CFD technique can be used to make an assessment of the change in airway resistance due to the MAD.

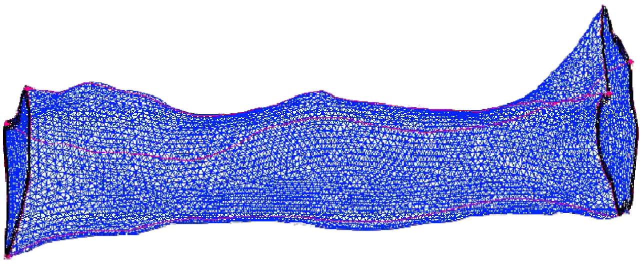

Figure 4 Upper Airway divided into discrete cells

Figure 4 presents an upper airway model divided into discrete cells. A typical upper airway model contains between 600.000 and 800.000 cells, depending on the complexity of the model. This amount of cells limits the cell Reynolds number and thereby minimises the numerical diffusion. Due to the narrowness of the upper airway region, the flow could be considered turbulent [6]. Therefore a turbulence model is used in the calculations. For these types of problem the k-ω has been used.

The methods as described above have been used to generate the models of all the patients in the study. The next section describes the results of this modelling.

3 RESULTS AND DISCUSSION

An overview of the patient data and the outcome of the clinical evaluation are given in Table 1. For every patient the age, sex and body mass index (BMI) is given. The clinical evaluation has been done through the assessment of the apnea-hypopnea index. This index lists the number of events per hour. An event is defined as a closure or near closure of the upper airway and can be determined from the polysomnography that registered the flow during sleep. An apnea or hypopnea is characteristed by a limitation in flow (hypopnea) or a complete cessation of flow (apnea). Also a decrease in snoring index is part of a clinical improvement especially in the non-apneic snorers (AHI<5).

No	age	sex	bmi	AHI MAD-	AHI MAD+	Clinical Improvement
Pat 1	48	M	27	24	1	yes
Pat 2	60	M	34	31	9	yes
Pat 3	57	M	25	14	2	yes
Pat 4	54	M	25	17	1	yes
Pat 5	58	F	34	23	5	yes
Pat 6	44	M	31	1	4	no
Pat 7	52	M	29	12	14	no
Pat 8	51	M	24	22	21	no

Table 1 Overview of patient data and clinical evaluation

For all the patients in the study three characteristics were considered in order to assess the efficiency of the MAD. The initial analysis considered the change in upper airway volume with and without the MAD. For both geometries (MAD, no-MAD) the resistance was assessed based on the patient specific boundary conditions (flow, pressure) obtained during the clinical test (polysomnography). The resistance equals the pressure difference Δp divided by the flow F as described in equation (1)

$$R = \frac{\Delta p}{F} \qquad (1)$$

Figure 5 presents velocity vectors in the upper airway for a patient without (left) and with (right) MAD. From this figure it can be seen that due to the increase in upper airway volume the velocity at the smallest cross sectional area decreases. This indicates a reduction in the resistance of the upper airway.

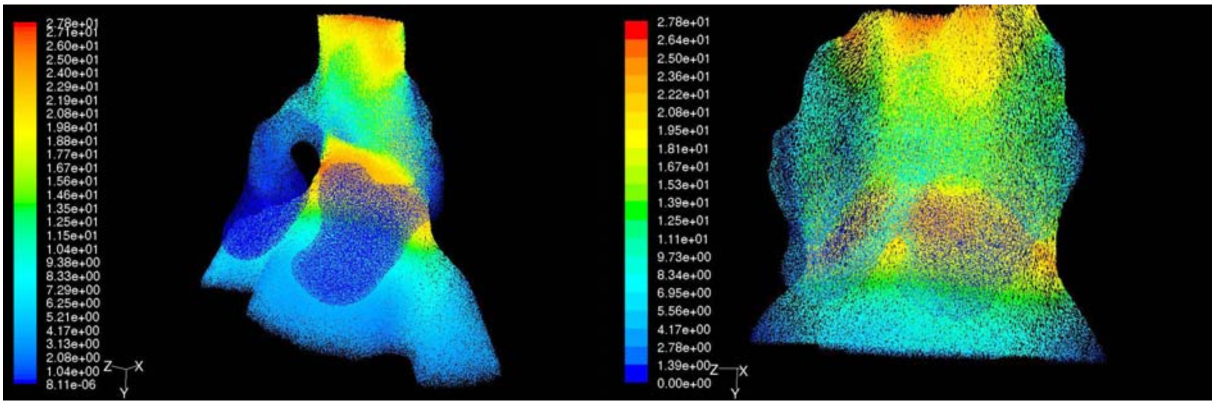

Figure 5 Velocity vectors (m/s) for the cases without (left) and with (right) MAD

The third topic that was examined were the anatomical characteristics of patients, we focused on the mandibular angle since this determines the actual horizontal advancement and the change in upper airway volume.

Figure 6 shows the 3D reconstruction of maxilla, mandibula and upper airway for a successfully treated patient on the left and for a patient who didn't clinically improve on the right.

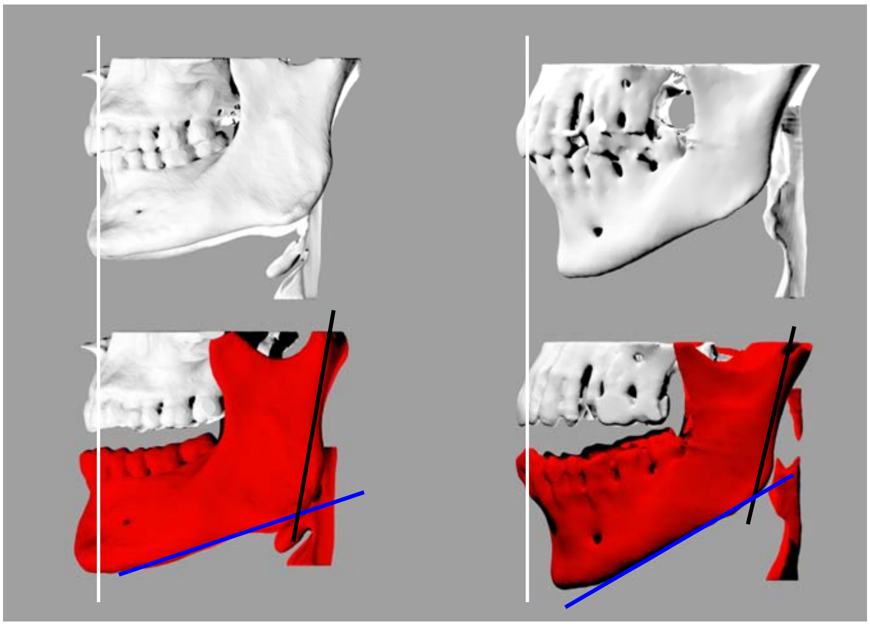

Figure 6 Sagital images of a succesfully treated patient (left) and an unsuccesfully treated patient (right)

The construction lines drawn in Figure 6 assist in the determination of the horizontal advancement and the mandibular angle. This process has been repeated for all patients. It could be seen from these reconstructed views that the actual horizontal advancement of the mandibula is larger in patients that improved clinically. This can be attributed to the fact that the muscle that determines the shape of the upper airway (Musculus Genioglossus) is attached to the forward part of the mandibula. Hence the movement of this part determines the change in upper airway volume.

No	ΔR (%)	ΔV (%)	Mandibular Angle (degrees)	Clinical Improvement
Pat 1	-56	28	110	yes
Pat 2	n/a	320	118	yes
Pat 3	-53	55	110	yes
Pat 4	-72	40	109	yes
Pat 5	-78	43	119	yes
Pat 6	5	0	138	no
Pat 7	n/a	-54	130	no
Pat 8	4	-6	135	no

Table 2 Overview of change in upper airway resistance, upper airway volume, the mandibular angle and the clinical improvement of all patients

Table 2 provides an overview of the change in upper airway resistance ΔR in percentage, the change in upper airway volume ΔV also in percentage, the mandibular angle in degrees and the clinical improvement. From this overview it can be seen that whenever an increase in upper airway volume is observed, the patient also clinically improves. This increase in volume coincides with a decrease in airway resistance indicating that the airway volume increase evenly over the entire length. When analyzing the anatomical characteristics it became obvious that patients that improved clinically had a smaller mandibular angle compared to the ones that did not improve. This finding coincides with the fact that the horizontal advancement of the mandibula is important for the change in upper airway volume as described previously.

4 CONCLUSIONS

The aim of this project was to investigate the possibility of predicting the effect of a MAD in advance to increase the treatment's success rate. In order to do so, 8 patients have been analyzed. For all these patients the change in upper airway volume and resistance as well as the mandibular angle were assessed. It turned out that whenever the upper airway volume increased by wearing the MAD also the patient improved clinically. This increase in upper airway volume coincided with a decrease in upper airway resistance. The anatomical assessment of the mandibular angle revealed that patients with a large angle are less susceptible to improvement in AHI when wearing a MAD.

It could be concluded that the assessment of a MAD with advanced anatomical imaging and computational fluid dynamics provided better insight into the mechanisms of the therapy and can assist in optimizing the patient's care.

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