Numerical airflow simulations: What do they tell us about our sleep?

Numerical simulation of airflow in the human upper airways of sleep apnea patients

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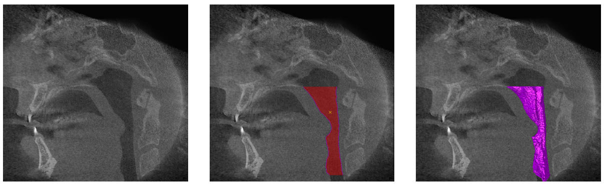
In Short

- Computational fluid dynamics allow the non-invasive investigation of flow features in flow volumes that cannot be measured like in the human upper airways.
- Simulated airflow can give a better understanding of upper airway obstructions and has potential as optimization tool for an effective patient individual treatment.
- Reconstructed patient specific airway geometries from tomographic medical imaging data serves as a base for the flow analysis.
- The accuracy of the airflow simulations depend on the type of model which themselves depend on the available computational resources.

The obstructive sleep apnea (OSA) is a sleep related breathing disorder, characterized by repetitive partial or complete closure of the pharyngeal lumen due to reversible soft tissue deformations. This results in an insufficient alveolar ventilation reducing the oxygen saturation in the blood. A small arousal from sleep is necessary to reactivate the tone of the upper airway musculature and to restore the airflow to the lung. The main symptom of OSA is daytime sleepiness, connected with reduced concentration, lack of drive and depression. OSA is also connected to a higher risk to die of cardiovascular diseases. Patients with untreated OSA have a reduced life expectancy with reduced life quality 1.
Treatment options are wearing a continuous positive airway pressure (CPAP) mask or a mandibular advancement appliance (MAA) during sleep. The first one prevents the pharynx from collapsing by establishing a positive pressure in the upper airways, the second one by a reversible rearrangement of the pharyngeal geometry by advancing the lower jaw and attached soft tissue to the front.

Within this project the pathophysiological process of upper airway collapses of OSA patients shall be investigated in a fluid dynamical point of view. Whereas it is impossible to perform detailed measurements of fluid dynamical properties like the airflow velocity and the pressure distribution within the living patient, we like to investigate the airflow in a computational fluid dynamical way using patient specific airway geometries.
In order to perform patient individualized numerical examinations of the airflow of OSA patients specific airway geometries are digitized based on three dimensional tomographic medical imaging data. The pharyngeal airspace is segmented and converted to a surface representation of triangular surface elements. Figure 1 outlines the airway reconstruction process exemplary on a cone beam CT image of an OSA patient, that was acquired in the process of mandibular advancement appliance production for OSA therapy.



***(a)** CT image* ***(b)** Segmentation* ***(c)** Triangulation*

***Figure 1:** Exemplary procedure of patient specific airway geometry reconstruction from three dimensional tomographic medical imaging data using a cone beam CT image of an OSA patient.*

The airflow in the human upper airways is simulated using the incompressible Navier-Stokes equations for Newtonian Fluids. These are a set of nonlinear partial differential equations of second order describing mass and momentum conservation of a flowing fluid. These equations are discretized and numerically solved for velocity and pressure in the computational domain.
The flow in the human upper airways is in the laminar-to-turbulent transitional regime. There exist different techniques to incorporate turbulent behavior in the computation, which enhance the computational costs. Ordered in decreasing accuracy the most used turbulence treatments are the Direct Numerical Simulation (DNS), the Large Eddy Simulation (LES) and the Reynolds Averaged Navier-Stokes simulation (RANS). The computational costs rise with the accuracy of the simulation type from RANS over LES to DNS.
Preliminary results were obtained on a patient data set with two geometries, one reconstructed from a cone beam CT image of a patient without treatment of OSA in its natural geometry and a second geometry of the same patient wearing a mandibular advancement appliance, hence having a reversible deformed airway geometry 3. These preliminary re-

sults in figure 2 show that a constriction of the airway geometry leads to an increase of the air velocity in both geometries, but the increase in flow velocity is halved by wearing the mandibular advancement appliance. An increase in the velocity is in general connected to a loss in pressure, this region is therefore a potential region of collapse. The simulations indicate that the pharyngeal geometry with mandibular advancement appliance is less prone to collapse as the one without, because of a lower pressure loss in the stream. Hence, numerical simulations of the airflow can give fluid dynamical explanations for therapy successes.

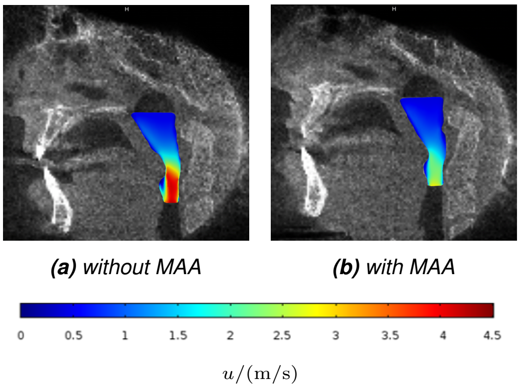


Figure 2: *The numerical simulation of the airflow velocity in the upper airways of an OSA patient is shown on the left for the patient without treatment and with wearing a MAA on the right.*

With the help of the HLRN the simulations in patient specific upper airways can be extended to Large Eddy Simulations that give a more realistic characterization of the laminar-to-turbulent transitional airflow for sleep apnea patients and help to get a better understanding of the pathophyiological flow features of upper airway collapses.

WWW

http://www.imt.uni-luebeck.de/research/image-computing/pharyngeal-airflow-simulation.html

More Information

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[2] P. Gurumurthy et al., In proceedings of *Biomedizintechnik/Biomedical Engineering*, (2017).

[3] C. Kluck et al., *Current Directions in Biomedical Engineering* **1**, 1 (2016), doi:10.1515/cdbme-2016-0003.