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Computational fluid dynamics endpoints for assessment of adenotonsillectomy outcome in obese children with obstructive sleep apnea syndrome

Haiyan Luo [a], Sanghun Sin [b], Joseph M. McDonough [c], Carmen R. Isasi [d], Raanan Arens [b], David M. Wootton [a,*]

[a] Department of Mechanical Engineering, The Cooper Union for the Advancement of Science and Art, 41 Cooper Square, New York, NY, USA
[b] Division of Respiratory and Sleep Medicine, Albert Einstein College of Medicine, The Children's Hospital at Montefiore, Bronx, NY, USA
[c] Division of Pulmonary Medicine, The Children's Hospital of Philadelphia, Philadelphia, PA, USA
[d] Department of Epidemiology & Population Health, Albert Einstein College of Medicine, Bronx, NY, USA

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ABSTRACT

Background: Improvements in obstructive sleep apnea syndrome (OSAS) severity may be associated with improved pharyngeal fluid mechanics following adenotonsillectomy (AT). The study objective is to use image-based computational fluid dynamics (CFD) to model changes in pharyngeal pressures after AT, in obese children with OSAS and adenotonsillar hypertrophy.
Methods: Three-dimensional models of the upper airway from nares to trachea, before and after AT, were derived from magnetic resonance images obtained during wakefulness, in a cohort of 10 obese children with OSAS. Velocity, pressure, and turbulence fields during peak tidal inspiratory flow were computed using commercial software. CFD endpoints were correlated with polysomnography endpoints before and after AT using Spearman's rank correlation (r_s).
Results: Apnea hypopnea index (AHI) decreases after AT was strongly correlated with reduction in maximum pressure drop (dP_{TAmax}) in the region where tonsils and adenoid constrict the pharynx (r_s=0.78, P=0.011), and with decrease of the ratio of dP_{TAmax} to flow rate (r_s=0.82, P=0.006). Correlations of AHI decrease to anatomy, negative pressure in the overlap region (including nasal flow resistance), or pressure drop through the entire pharynx, were not significant. In a subgroup of subjects with more than 10% improvement in AHI, correlations between flow variables and AHI decrease were stronger than in all subjects.
Conclusions: The correlation between change in dP_{TAmax} and improved AHI suggests that dP_{TAmax} may be a useful index for internal airway loading due to anatomical narrowing, and may be better correlated with AHI than direct airway anatomic measurements.

1. Introduction

Obstructive sleep apnea syndrome (OSAS) is a respiratory disorder characterized by narrowing of the pharyngeal airway, resulting in repeated episodes of flow limitation or complete cessation, associated with oxygen desaturation and sleep disruption (Stradling and Davies, 2004). OSAS is common in children and may affect 1–4% of the general pediatric population (Lumeng and Chervin, 2008) and up to 50% of obese children (Kalra et al., 2005; Marcus et al., 1996; Silvestri et al., 1993). Magnetic resonance imaging (MRI) studies of the upper airway (UA) confirm that children with OSAS frequently have adenotonsillar hypertrophy and a structurally narrowed pharynx (Arens et al., 2002, 2001) located in the region where the tonsils and adenoid overlap (Arens et al., 2003). The American Academy of Pediatrics (AAP) recommends considering adenotonsillectomy surgery (AT) as the first treatment for children with OSAS (American Academy of Pediatrics, 2002). But the persistence of OSAS after AT is common particularly in obese children and may reach 50% (Mitchell and Boss, 2009; Mitchell and Kelly, 2007; Suen et al., 1995; Tal et al., 2003), which suggests that a clinical tool for predicting the outcome of AT would be valuable.

Computational fluid dynamics (CFD) is an engineering tool that can simulate detailed three-dimensional airflow dynamics and the resulting pressure distributions driven by anatomical narrowing, and may be helpful for comparing different surgical approaches to airway restriction (Mylavarapu et al., 2013). The effects of AT on airway pressure drop and flow resistance have been modeled by

* Corresponding author. Tel.: +1 01 212 353 4393; fax: +1 01 212 353 4341.
E-mail address: wootto@cooper.edu (D.M. Wootton).

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CFD based on pre- and post-surgery MRI (Mihaescu et al., 2008). However, few patients were studied so that statistical analysis could not be performed. But image-based CFD model endpoints have been strongly correlated with clinical benefit of mandibular advancement devices (De Backer et al., 2007; Zhao et al., 2013), and more weakly correlated with polysomnography endpoints (Cisonni et al., 2013; Vos et al., 2007; Wootton et al., 2014).

In the present retrospective cohort study, we hypothesize that CFD model endpoints will correlate well with treatment response of AT as measured by a decrease in the apnea-hypopnea index (AHI) from an overnight polysomnography study. MRI, physiologic data, and CFD data were utilized to calculate the velocity and air pressure distribution in ten obese children with OSAS, before and after AT. Based on these models we analyzed the correlation between AT treatment response and airway geometrical changes, minimum surface pressure, local air pressure drops in different airway segments, and airway pressure-flow ratio.

2. Methods

2.1. Subjects and procedures

The study was approved by the Committee of Clinical Investigations at Albert Einstein College of Medicine (Protocol #2005-578). Informed consent was obtained from each subject and or/parent. Ten obese adolescent subjects were recruited at the Children's Hospital at Montefiore using the following criteria: (1) diagnosed with OSAS by overnight polysomnography, (2) normal development and intact adenoid and tonsils, and (3) adenotonsillar hypertrophy indicating AT surgery. Subjects were a subset of subjects from a larger study of anatomical effects of AT (Nandalike et al., 2013). Before and after surgery all subjects underwent polysomnography and MRI. Mean interval between AT and second polysomnography was 4.4 months, and between AT and second MRI was 4.8 months. Overnight polysomnography (Xltek, Oakville, ON, Canada) was performed at the Sleep Disorders Center at the Children's Hospital at Montefiore. OSAS was determined if the obstructive apnea hypopnea index (AHI) was ≥ 2/hour. Resting respiratory flow rate was measured in supine position with a pneumotachometer (RSS 100HR Research; Hans Rudolph) on the day of each imaging study. After discarding unusually short or long breaths at least ten normal tidal breaths were averaged, and average maximum inspiratory flow rate was calculated. Bilateral nasal resistance curves were measured using anterior rhinomanometry (NR-6 Research, GM Instruments). Three measurements of four breaths with at least 150 Pa pressure drop were acquired (Clement and Gordts, 2005). Average Rohrer coefficients for each nasal passage were used to calculate nasal resistance and air pressure in the choanae at peak inspiratory flow.

Subjects underwent upper airway MRI, and T-1 & T-2 weighted axial images were obtained in the Department of Radiology at the Children's Hospital at Montefiore, using a Philips 3.0 T Achieva scanner with 16 channel surface array coil (SENSE XL; Philips Medical System, Best, The Netherlands) as previously described (Nandalike et al., 2013). Subjects were awake during imaging and positioned supine with head in neutral position, i.e., the Frankfort plane perpendicular to the table. The slice thickness was 3 mm with 0.3 mm gap and 0.5×0.5 mm^2 pixel size.

Seventeen subjects from the original study were excluded in cases where nasal resistance data was not available both before and after surgery, typically due to nasal obstruction, and in cases where subject motion in an MRI study made accurate surface reconstruction for CFD modeling impossible. All subjects not excluded ($N=10$) were studied as a single cohort with one-time follow-up.

2.2. Image processing and CFD mesh generation

The airway from nares to trachea was reconstructed from the axial image stack using commercial medical imaging software (MIMICS, Materialise). Segmented slices were reconstructed with a volume-preserving smoothing algorithm to generate a three-dimensional model (Fig. 1). Airway cross-sections perpendicular to the airway direction were defined at the choanae, at the minimum cross-section of the region where tonsils and adenoids constrict the airway, and the trachea. The 3D model was imported into commercial CFD meshing software (Gambit, ANSYS, Lebanon, NH, USA) to create an unstructured tri/tetrahedral mesh with 1.6–2.6 million cells.

2.3. Fluid mechanics parameters and model solution

A commercial CFD package (Fluent ANSYS 14, ANSYS) was used to solve the flow governing equations, ignoring airway wall motion. Both pre- and post-surgery

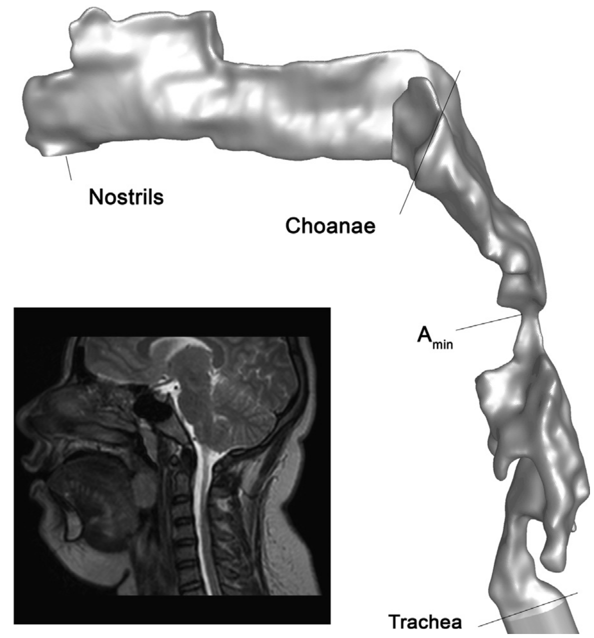

Fig. 1. 3D upper airway model of subject 4 pre-surgery based on reconstructed segmented MR axial images. Anatomical locations along the airway model are shown in references. A_{min} is the location of minimum cross-section where tonsils and adenoids constrict the pharynx; in this subject A_{min} is located between the tonsils in the retrolingual pharynx. Inset: midline sagittal MR image of subject 4.

flow simulations were performed at the maximum inspiratory flow rate computed from pre-surgery waveform flow data. Due to the area restriction, a turbulent jet is expected downstream of the restriction (Young, 1979; Young and Tsai, 1973), so a low Reynolds number k–ω turbulence model was used to solve for turbulence quantities (Wilcox, 1998). The computer simulation pressure field accuracy has been verified with experimental data from in vitro (Xu et al., 2006) and in vivo (Wootton et al., 2014) airway models.

2.4. Endpoints and statistical methods

Several endpoints were derived from the CFD models. Area-averaged air pressures were computed at the choanae (P_{CH}) and trachea (P_{TR}), as well as representative cross-sections in the nasopharynx, velopharynx, retrolingual pharynx, and hypopharynx. Minimum airway wall pressure in the region where tonsils and adenoids constrict the airway (P_{TA}) and minimum pressure in the pharynx (P_{PM}) were identified. Pressure drop from the choanae through the maximum constriction area ($dP_{TAmax}=P_{CH}-P_{TA}$) was derived from the CFD model. Minimum airway pressure in the region where tonsils and adenoids maximally constrict the airway (P_{min}) was computed from the measured nasal resistance and the pressure drop: $P_{min}=-dP_{rhino}–dP_{TAmax}$. Pressures and pressure drops require a clinical measurement of volume flow rate $\dot{V}$ and are somewhat sensitive to $\dot{V}$, therefore the pressure drop to flow ratio was also computed from the CFD data as follows:

$$PQR_{TAmax} = \frac{dP_{TAmax}}{|\dot{V}|} \tag{1}$$

An anatomical-based estimate of PQR_{TAmax}, ignoring viscous losses and secondary flow effects, was derived from Bernoulli's equation:

$$PQR_{TA,Bernoulli} = \tfrac{1}{2}\rho|\dot{V}|(A_{min}^{-2} - A_{CH}^{-2}) \tag{2}$$

where A_{min} and A_{CH} are the minimum area where tonsils and adenoids constrict the pharynx, and the choanae cross-section area, respectively, and ρ is the density of air.

Clinical, anatomical, and CFD endpoint improvements were normalized by their pre-surgery values, e.g. AHI decrease$=(AHI_{pre\text{-}AT} - AHI_{post\text{-}AT})/AHI_{pre\text{-}AT}$. Spearman's correlation coefficients (r_s) and p-values were computed between AHI decrease as a measure of OSAS severity, and CFD and anatomical endpoint improvements (Matlab).

3. Results

3.1. Subjects and clinical outcomes

Demographic and sleep study values are shown in Table 1. Mean subject age was 13.4 ± 1.7 years; 5 subjects were female.