IMAGE-BASED MODELING OF UPPER AIRWAY FLOW IN CHILDREN WITH OBSTRUCTIVE SLEEP APNEA

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INTRODUCTION

Obstructive sleep apnea syndrome (OSAS) may affect up to 2% of children, and is associated with lymphoid hyperplasia, craniofacial anomalies, and neurological disorders. Recently we have developed fuzzy connectedness image processing methods to automatically segment the upper airway and surrounding anatomy. We have shown that children with OSAS but no apparent craniofacial or neurological disorders have decreased upper airway volume, and decreased mean and minimum airway cross-sectional areas, compared to controls [1,2].

Surgical removal of tonsils and adenoids often relieves symptoms of OSAS, but is occasionally ineffective. Automated segmentation combined with image-based flow modeling could potentially be used clinically to assess the likelihood that tonsil and adenoid reduction will be effective. In this research we explore the physiological significance of upper airway anatomy on flow resistance, and the importance of cross-sectional area and cross-sectional aspect ratio on resistance and pressure drop.

METHODS

20 OSAS children were recruited through the Sleep Disorders Center after OSAS was diagnosed by polysomnography and compared to 20 matched controls. MRI was performed with a 1.5 T scanner. Sequential T2 spin-echo axial sections were obtained along the airway from the orbital cavity to the larynx. The airway dimensions were determined after segmentation and 3D reconstruction using 3DVIEWNIX (MIPG Dept., University of Pennsylvania).

Computational fluid dynamics software (CFD) was used to calculate the effects of airway anatomical differences on flow resistance and pressure drop at peak inspiratory flow rates. Two types of models were generated from the segmented images. (1) Area-length curves of the airway from the nasopharynx through the epiglottis were used to generate 2D axisymmetric flow models. These models were used to compute the effect of area variation of flow resistance and pressure. (2) Cross-sections of the segmented 3D reconstruction were created, perpendicular to the airway centerline, and exported to a file. For each cross-section, an elliptical approximation was computed using least-squared error fitting in the plane of the cross-section. The sequence of ellipses was used to generate an approximate 3D model, using commercial software (Gambit 2, Fluent, Inc). The elliptical model was used to evaluate additional resistance due to airway curvature and cross-section aspect ratio.

Velocity, pressure, and turbulence fields were calculated for steady flow at peak inspiration, using a commercial software package (Fluent 6/Gambit 2, Fluent, Inc). A two-equation turbulence model, the low-Reynolds number k-ω model, was used since Reynolds number was sufficient to generate post-stenotic turbulence at peak flow]. Uniform velocity was imposed at the inlet, with 5% turbulence intensity and low dissipation rate. Grid convergence was verified, and independence of turbulence boundary conditions was demonstrated. Model endpoints were maximum pressure drop through the upper airway, and flow resistance.

RESULTS

OSAS airways were significantly narrower than control airways near the tonsils and adenoids, leading to larger and more concentrated pressure drop (figure 1). OSAS subject models had approximately 10-fold higher pressure drop than area profiles from controls, and concomitant 10-fold increase in resistance. Segment pressure drop in OSAS subjects was comparable to critical airway closure pressures reported in the literature.

Pressure drop in the axisymmetric models could be almost completely predicted by centerline velocity using Bernoulli's equation. Boundary layer displacement of the core flow caused significant increase in centerline velocity, compared to average velocity

The elliptical airway model showed additional resistance, leading to approximately 20% higher pressure drop than the axisymmetric model (figure 3) when cross-section aspect ratio and airway curvatures were added.

CONCLUSIONS

Anatomical differences between upper airways lead to significantly higher airway resistance in OSAS children compared to children with normal airway anatomy. Models based on airway area variation alone predicted pressure drop to first order, while effects of aspect ratio and curvature significant increases in pressure drop. Future work will include more accurate representations of cross-section geometry for comparison to ellipse-based 3D models.

ACKNOWLEDGEMENTS

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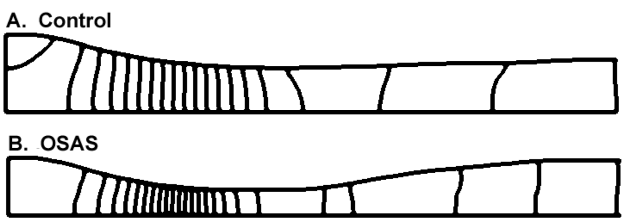

Figure 1. Axisymmetric airway models (centerline to radius) with pressure contours.

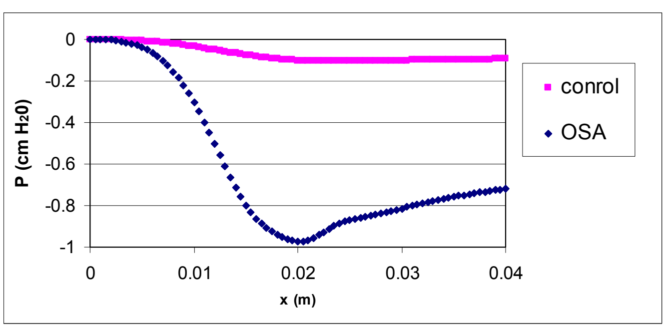

Figure 2. Comparison of pressure drop from the nasopharynx through epiglottis for average control airways vs. average OSAS airways.

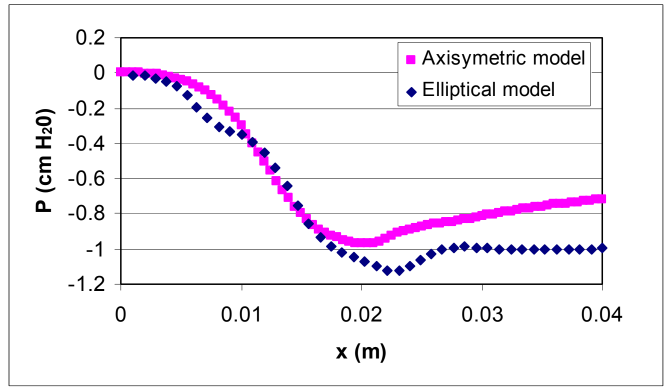

Figure 3. Comparison of pressure drop in axisymmetric vs. 3D elliptical models.