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Computational Modeling of Airway Obstruction in Sleep Apnea in Down Syndrome: A Feasibility Study

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Author Contributions

Goutham Mylavarapu, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Dhananjay Subramaniam**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Raghuvir Jonnagiri**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Ephraim J. Gutmark**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Robert J. Fleck**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Raouf S. Amin**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Mohamed Mahmoud**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Stacey L. Ishman**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work; **Sally R. Shott**, study design, analysis of data, drafting and revision of document, final approval of paper, agreeable to be accountable to all aspects of the work.

Abstract

Current treatment options are successful in 40% to 60% of children with persistent obstructive sleep apnea after adenotonsillectomy. Residual obstruction assessments are largely subjective and do not clearly define multilevel obstruction. We endeavor to use computational fluid dynamics to perform virtual surgery and assess airflow changes in patients with Down syndrome and persistent obstructive sleep apnea. Three-dimensional airway models were reconstructed from respiratory-gated computed tomography and magnetic resonance imaging. Virtual surgeries were performed on 10 patients, mirroring actual surgeries. They demonstrated how surgical changes affect airflow resistance. Airflow and upper airway resistance was calculated from computational fluid dynamics. Virtual and actual surgery outcomes were compared with obstructive apnea-hypopnea index values. Actual surgery successfully treated 6 of 10 patients (postoperative obstructive apnea-hypopnea index <5). In 8 of 10 subjects, both apnea-hypopnea index and the calculated upper airway resistance after virtual surgery decreased as compared with baseline values. This is a feasibility and proof-of-concept study. Further studies are needed before using these techniques in surgical planning.

Keywords

obstructive sleep apnea; Down syndrome; computational fluid dynamics; virtual surgery; airway modeling

Operations for obstructive sleep apnea (OSA) that persists after adenotonsillectomy have only 40% to 60% success.¹⁻⁴ Computational modeling of the airway could improve these outcomes by tailoring surgery to fit each patient.

Computational fluid dynamics (CFD) simulations use numeric analysis and algorithms to compute flow parameters such as velocity, turbulence, airflow pressure, and wall shear stress. This CFD modeling has been used to describe pulmonary airflow dynamics^{5,6} and was validated in an airway phantom.⁷

In this pilot study, we explore the use of virtual surgery (VS; modeling and simulation) to evaluate operations in 10 children with Down syndrome with persistent OSA. This was achieved in 3 steps:

1. generate anatomically accurate and patient-specific airway geometry (baseline) from magnetic resonance imaging (MRI) or computed tomography (CT scans),
2. virtually modify the shape of airway, mirroring actual surgery, and
3. perform CFD simulations to evaluate the resistance to airflow in the baseline and modified airways.

VS allows for assessment of airflow changes when surgery is performed at multiple airway sites and how these changes affect upper airway resistance (UAR). Since UAR is related to airway sites of obstruction, it may be linked to airway collapsibility. Use of VS has been demonstrated in adults with subglottic and tracheal stenosis.⁸ Outcomes of VS and actual surgery were compared.

Methods

In this Institutional Review Board–approved study (Cincinnati Children’s Hospital Medical Center 2010-2332), respiratory-gated MRI and CT scans were obtained under drug-induced sleep conditions. These scans were used to reconstruct baseline airway geometry. In each scan, airway boundaries were identified. Three-dimensional airway geometry was generated with Mimics medical imaging software (Materialise, Leuven, Belgium). Two ear/nose/throat surgeons performed VS on each baseline airway model, intended to reflect airway geometry changes that mirrored those from the actual operations performed. The modified VS airway geometries were then reconstructed.

These geometries were then discretized into small tetrahedral cells with the meshing software TGrid (ANSYS, Canonsburg, Pennsylvania). CFD was used to predict the flow distribution in the airway lumen by solving the flow-governing equations at each cell. Simulations were performed to approximate an expiratory flow rate of 10 L/min (typical normal breathing) with Fluent CFD software (ANSYS, Canonsburg, Pennsylvania). UAR was calculated for all baseline and VS models and defined as the pressure difference (P) between choanae and the base of tongue, required to provide a desired volumetric flow rate (Q), $UAR = P/Q$. The outcomes of the surgery were defined as success if the postoperative obstructive apnea-hypopnea index (oAHI) was <5 events/hour. A surgical failure was defined when the oAHI did not decrease <5 events/hour. Agreement of the CFD with surgical outcome was defined as being present when a similar change in the oAHI and predicted CFD resistance was calculated, regardless of the direction of change.

Results

Actual surgery was successful (defined by postoperative oAHI <5 events/hour) in 6 of 10 patients. Changes in oAHI and UAR, as calculated by CFD for pre- and postoperative modeling, matched well for 8 of 10 patients (Table 1).

VS is demonstrated in patient 9 (20 years). Despite previous adenotonsillectomy, he had macroglossia, retroglossal obstruction with glossoptosis, enlarged lingual tonsils, and hypopharyngeal collapse. He underwent lingual tonsillectomy, midline posterior glossectomy, suture tongue suspension, and hyoid myotomy with suspension. His oAHI decreased from 93.1 to 29.8 events/hour; REM sleep increased from 9.2% to 20.1%; and arousal index decreased from 76.9 to 40 arousals/hour.

Figures 1 and 2 show the sagittal CT scans and reconstructed 3-dimensional airway geometries, respectively, for baseline and VS performed on patient 9. The changes in UAR for the multiple operations treating the base of tongue (with enlargement of the retroglossal airspace by 2 and 4 mm) were evaluated with CFD. Both variations of tongue VS resulted in a 46% and 48% decrease in resistance, respectively, when compared with baseline. The palate-shortening VS alone, based on the baseline, also resulted in a 30% reduction in resistance.

VS was repeated in 9 additional patients to determine if the UAR calculated from this methodology agreed with the observed surgical outcomes. The results for all 10 patients are

summarized in Table 1, with good agreement in 8 of 10 patients. For the 6 successful surgery cases (patients 1–6), resistance substantially decreased, as predicted by VS. Two patients in the unsuccessful surgery group (patients 8 and 9) had small to no change in their resistance. There is lack of agreement between surgical outcomes and computational modeling in 2 of 10 patients. Patient 7 had an increase in pre- to postoperative oAHI, but CFD predicted a decrease in UAR. Patient 10 had a decrease in both oAHI and UAR, but the changes were not proportional.

Discussion

Studies show that adenotonsillectomy does not always cure OSA, even in typical children. In patients with moderate to severe OSA, upper airway obstruction commonly occurs at >1 anatomic level. The use of computational modeling and VS could assist with surgical planning, specifically to stratify primary versus secondary sites of obstruction when multilevel obstruction is seen.

Patient 9 had only tongue surgery, without palate surgery, resulting in an oAHI decrease from 93.1 to 29 events/hour. This represents an improvement but not a cure. The computational modeling and VS suggest that subsequent surgery on his soft palate may further improve his OSA.

Further research is needed before we can clinically use this technology. Only 8 of 10 patients had good agreement between VS and actual surgical outcomes. This could be due to imaging artifacts (improper gating), VS (surgeon bias), and computational modeling (not accounting for interaction between airflow and surrounding soft tissue, as in an excessively dynamic airway). Surgical changes in anatomy used for VS also needs confirmation with postoperative MRI.

Conclusion

Computational modeling of the upper airway represents a new frontier in the diagnosis and surgical management of pediatric OSA. Modeling can add significant value to existing clinical assessments and surgical decision making. The VS carried out here and the resultant airway modeling with CFD allow us to understand the qualitative and quantitative effects of surgical procedures on airway resistance.

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Figure 1.
Midsagittal computed tomography scans for (a) baseline; (b) palatoplasty; (c) tongue surgery, 2 mm; (d) tongue surgery, 4 mm.

Figure 2.

Three-dimensional airway geometries for (a) baseline and (b–d) 3 virtual surgery postoperative scenarios, corresponding to those in Figure 1. Baseline airway is shown in red, and the airway lumen due to surgery is shown in highlighted regions in orange.

Virtual Surgery Summary^a.

Table 1

Patient	Type of Surgery	Sleep Studies: oAHI (Events/h)		Virtual Surgery: UAR (Pa/L/min)		Agreement
		Presurgery	Postsurgery	Presurgery	Postsurgery	
1	Revision adenoidectomy + vallecular cyst removal	13.3	0.9	21.46	1.09	Yes
2	LT + MPG	5.7	2.7	29.50	0.33	Yes
3	MPG	5	4.1	5.40	3.20	Yes
4	Revision adenoidectomy	6.3	0.4	10.17	0.16	Yes
5	Revision adenoidectomy + GGS + MPG	142	3.4	1.18	0.06	Yes
6	MPG + GGS + LT	9.4	1.8	2.72	0.44	Yes
7	MPG + palatoplasty + hyoid	34	44	23.21	1.87	No
8	Palatoplasty + MPG	20	19	19.31	18.19	Yes
9	MPG + GGS + LT + hyoid	93	29.8	2.44	1.30	Yes
10	LT + MPG + GGS	19.7	11	149.61	2.87	No

Abbreviations: GGS, genioglossus suspension; LT, lingual tonsillectomy; MPG, midline posterior glossectomy; oAHI, obstructive apnea-hypopnea index; UAR, upper airway resistance.

^aChange in oAHI from sleep study versus change in UAR as calculated by computational fluid dynamics with surgery.