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Original Article

# Functional respiratory imaging as a tool to assess upper airway patency in children with obstructive sleep apnea

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ABSTRACT

*Objective:* We aim to investigate if anatomical and functional properties of the upper airway using computerized 3D models derived from computed tomography (CT) scans better predict obstructive sleep apnea (OSA) severity than standard clinical markers.
*Methods:* Consecutive children with suspected OSA underwent polysomnography, clinical assessment of upper airway patency, and a CT scan while awake. A three-dimensional (3D) reconstruction of the pharyngeal airway was built from these images, and computational fluid dynamics modeling of low inspiratory flow was performed using open-source software.
*Results:* Thirty-three children were included (23 boys; mean age, was 6.0 ± 3.2 y). OSA was diagnosed in 23 patients. Children with OSA had a significantly lower volume of the overlap region between tonsils and the adenoids (median volume, 1408 mm compared to 2173 mm; $p = 0.04$), a lower mean cross-sectional area at this location (median volume, 69.3 $mm^2$ compared to 114.3 $mm^2$; $p = 0.04$), and a lower minimal cross-sectional area (median volume, 17.9 $mm^2$ compared to 25.9 $mm^2$; $p = 0.05$). Various significant correlations were found between several imaging parameters and the severity of OSA, most pronounced for upper airway conductance ($r = -0.46$) ($p < 0.01$) for correlation between upper airway conductance and the apnea-hypopnea index. No differences or significant correlations were observed with clinical parameters of upper airway patency. Preliminary data after treatment showed that none of the patients with residual OSA had their smallest cross-sectional area located in segment 3, and this frequency was significantly lower than in their peers whose sleep study normalized (64%; $p = 0.05$).
*Conclusion:* Functional imaging parameters are highly correlated with OSA severity and are a more powerful correlate than clinical scores of upper airway patency. Preliminary data also showed that we could identify differences in the upper airway of those subjects who did not benefit from a local upper airway treatment.



## 1. Introduction

Obstructive sleep apnea (OSA) is a prevalent disorder affecting 1% to 4% of the general pediatric population [1]. However, this prevalence is much higher, exceeding 50% in children with specific risk factors including obesity and Down syndrome [2,3]. OSA in children also is associated with significant complications affecting the developing nervous and cardiovascular systems and should be correctly treated [4].

The main anatomic risk factor for pediatric OSA is adenotonsillar hypertrophy, but other factors such as, craniofacial abnormalities, obesity, and alterations in neuromotor tone also may play a role. Second, residual disease after adenotonsillectomy is present in a large proportion of children [5]. Although indices of nocturnal breathing improve in the majority of patients after adenotonsillectomy, there is a subset of patients who do not significantly improve and need to have justified surgery. In view of several non surgical alternatives, one of the challenges in this field will be to closely match the anatomic characteristics of an individual patient with

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the most appropriate treatment. A meta-analysis showed that the association between a clinical score of tonsillar hypertrophy and the severity of OSA is weak [6]. A number of imaging studies mainly using magnetic resonance imaging (MRI) have investigated the relation between upper airway structural anatomy and OSA severity [7–14]. Converting these images to three-dimensional (3D) models enables calculation of specific volumes of the upper airway but also enables the application of computational fluid dynamics (CFD). This method can derive additional functional and quantitative properties of the upper airway such as local resistances.

It was shown that these CFD parameters predicted the severity of OSA in adult patients and a response to treatment [15–17]. In children, CFD has mainly been used to investigate physiological changes in intra luminal pressures and resistances during obstruction rather than as a parameter of OSA severity or as a tool for treatment selection [18,19]. The aim of our study was to evaluate upper airway characteristics by using ultra low dose computed tomography (CT) scans, and computational fluid dynamics in children with sleep-disordered breathing. Furthermore, using preliminary data we also investigated if these imaging parameters could predict treatment outcome.

## 2. Methods

### 2.1. Study population

Consecutive children and adolescents between ages three and 16 years were referred to the Pediatric Sleep Lab of the Antwerp University Hospital for suspected OSA and were included between January 2011 and May 2012. All children had to be free of acute disease at the moment of sleep screening, and subjects with neuromuscular disease or any genetic or craniofacial syndrome were excluded. The Ethical Committee of the Antwerp University Hospital approved this study and informed consent was obtained from the subjects and their parents.

### 2.2. Questionnaire and physical examination

The parents completed a standardized questionnaire regarding sleep and respiratory co morbidities. Tonsillar size was rated by two authors (A.B. and S.V.) using the Brodsky scale [20]. A score of 0 was given for tonsillectomy. Tonsillar hypertrophy was scored with tonsil size >2. Modified Mallampati scale also was assessed [21]. Height and weight were measured according to standardized techniques. Body mass index was calculated as weight in kilograms over height in $m^2$ and was further analyzed as *z* scores.

### 2.3. Polysomnography

All subjects underwent polysomnography (Brain RT, OSG, Rumst, Belgium) according to standardized criteria. All tracings were manually scored using the American Academy of Sleep Medicine guidelines [22]. OSA was defined if obstructive apnea index was $\geqslant 1$ or if obstructive apnea-hypopnea index (OAHI) was $\geqslant 2$. Other parameters of interest included mean oxygen saturation ($<SaO_2>$), $SaO_2$ nadir, oxygen desaturation index (ODI), and arousal index.

### 2.4. CT scan

All patients underwent a CT scan to evaluate upper airway geometry. Scanning was performed with patients in supine and neutral position. The scan was performed using a GE LightSpeed 64-slice CT scanner with an average acquisition time between two and five seconds. This time resulted in a dataset containing an average of 350 to 400 DICOM images, all images having an in-plane spatial resolution of 0.3 mm and reconstructed with a slice increment of 0.5 mm. Because the main interest was to obtain images discriminating air in the airways from the surrounding soft tissue, all CT scan examinations were performed with an adapted low-dose scan protocol. This dose was achieved using an 80-kV setting, a modulated mA dosage depending on anatomic configuration (less dose in anatomic short-axis and more dose in the long-axis direction), and by using a limited scan range to the strictly minimal anatomic limits.

### 2.5. Upper airway morphology extraction from CT scan

The acquired DICOM images were processed using a commercial software package (Mimics 15.0, Materialise). Subsequently, a segmentation of the upper airway was done using the Hounsfield Unit (HU) of each voxel in the DICOM images as a discriminatory parameter, making a binary distinction between air and solid structures. The HU is a value for the radiodensity of the tissue and reaches from −1024 to 3071. Characteristic values on the Hounsfield scale are −1024 HU and 1000 HU, respectively corresponding with air and bone. Segmentation was performed from the nares to the first thoracic vertebra. The segmented region was then converted to a 3D model using a contour interpolation algorithm. Because this model is based on a segmentation of (near) cubic pixels, a staircasing effect can result. Using an appropriate smoothing algorithm with volume compensation, the 3D model was converted to a smooth realistic model without loss of patient-specific morphology of the upper airway. This model was then used for detailed analysis of the anatomical parameters, volume meshing, and CFD simulation. The following parameters were calculated, effective upper airway volume and minimal and mean cross-sectional area. Effective upper airway volume, is defined as the total upper airway volume, excluding the regions where there is almost no flow such as the sinuses and the air pockets close to the vocal cords. The upper airway was then divided in the following regions (Fig. 1), nostril to bottom of inferior turbinate (segment 1), bottom of inferior turbinate to choanae (segment 2), choanae to tip of uvula (segment 3), uvula to epiglottis (segment 4) and epiglottis to the first thoracic vertebra (segment 5). Volumes of these segments also were calculated, and the location of the minimal cross-sectional area was recorded.

### 2.6. Upper airway characteristics extraction from CFD

The 3D model obtained after segmentation was divided into discrete cells to form a hexahedral dominant computational domain (SnappyHexMesh 2.0.1, OpenCFD Ltd, UK). The cells volumes were in the order of $1e^{-14}$–$1e^{-8}$ $m^3$. The mesh was not aligned to the axial flow direction and the cells were extra refined near the boundaries, which resulted in a computational grid of the upper airway typically consisting of approximately 800,000 computational cells. This 3D mesh was exported and read into a custom Reynolds Average Navier Stokes CFD solver based on OpenFOAM 2.0.1 (OpenCFD Ltd, UK).

The following were boundary conditions that were set to the model:

(1) a pressure outlet at the outlet surface of the larynx of −20 Pa,
(2) a pressure inlet at the inlet surface at the botrils of 0 Pa,
(3) non impermeable walls (no-slip conditions) for the sides of the upper airway.

Pressure-based boundary conditions were used, as this enables the simulation of the flow demand for the wide range of patient ages and sizes. Second-order discretization schemes were used