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Modeling Congenital Nasal Pyriform Aperture Stenosis Using Computational Fluid Dynamics

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Abstract

Objectives—Congenital nasal pyriform aperture stenosis (CNPAS) is a rare cause of airway obstruction in the neonate. Computational airway modeling has not been done in neonates and young infants to understand the impact of stenosis on functional nasal airflow. In this study, we 1) applied computational fluid dynamics (CFD) model to the airway of a neonate with CNPAS and 2) compare airflow dynamics of a normal and CNPAS airway.

Methods—Three-dimensional models of the nasal airway of a normal neonate and a neonate with CNPAS were created using computed tomography scans of the facial bones. Measured anatomic parameters included volume, surface area, and cross-sectional area. CFD simulation was then performed. Simulated flow parameters included pressure, average velocity, and resistance.

Results—The neonate with CNPAS had a lesser volume (2.74cm³ vs. 4.50cm³) and surface area (18.8cm² vs. 45.5cm²) than the normal airway. The CNPAS airway had a lesser **bilateral** cross-sectional area and average cross-sectional velocity throughout the length of the model. While there is a large pressure drop in the normal airway immediately after the entry point, the pressure drop in the CNPAS airway occurs more posteriorly. The total nasal resistance was approximately eight-fold greater in the CNPAS airway than the normal.

Conclusions—CFD analysis can be performed on airways of neonates with nasal obstruction, such as in CNPAS. A CFD model may help characterize severity of airway obstruction as it can predict the three-dimensional pattern of airflow. Determining the role of CFD in clinical management of CNPAS requires further investigation.

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Keywords

pediatric airway; congenital pyriform aperture stenosis; airway modeling; fluid dynamics

Background

Congenital nasal pyriform aperture stenosis (CNPAS) is a rare cause of airway obstruction in the neonate. The condition is characterized by overgrowth of the nasal process of the maxilla into the nasal cavity, causing a narrowing of the pyriform aperture (PA) [1]. The diagnosis is suspected in the neonate presenting with poor respiration, cyclical cyanosis, feeding difficulties, and nasal obstruction. The diagnosis can be confirmed by nasal endoscopy and computed tomography [2]. The degree of airway stenosis and the severity of the resulting symptoms can vary greatly among patients.

This variability complicates treatment approach to CNPAS. Milder cases respond to conservative treatment, as the stenosis improves with age [3, 4]. Conservative measures include nasal humidifiers, nasal decongestants, treatment of reflux, and an oral airway [4, 5]. Those who fail conservative airway management, indicated by continued respiratory difficulty and poor weight gain, may require interventions such as endotracheal intubation, feeding tubes, or more aggressive interventions such as surgery [6, 7]. While the decision to proceed to more aggressive treatment is clinical, previous studies have attempted to identify the patients more likely to require surgical treatment by using CT-measured nasal cavity dimensions such as PA width or maxillary-nasal angle as predictors [5, 8]. However, the correlation between nasal cavity dimensions and clinical symptoms is unclear [9]. This may be because one or two dimensions are unlikely to be a satisfactory representation of a complex three-dimensional (3-D) space such as the nasal airway. Appropriate surgical procedure, decision to proceed with surgery, and outcomes are mixed and continue to be debated [4, 9, 10].

Computational fluid dynamics (CFD) modeling has been used to study normal and pathological conditions in the adult nasal airway [11–15]. Use of a CFD model may assist in assessing the functional airway in CNPAS patients. CFD analysis begins with the construction of a virtual model of the airway using a CT scan. Then, a simulation of flow through the model is created by numerically solving the Navier-Stokes equations describing fluid flow. The output parameters of the simulation (e.g., velocity, pressure) describe the characteristics of the flow at various points within the airway [16]. Thus, a CFD model accounts for the full 3-D architecture of the nasal airway. It can predict flow patterns locally as well as resistance to flow across the length of the airway. CFD may potentially provide objective information on the degree of nasal airflow obstruction and assist in therapeutic decision-making for CNPAS patients. To our knowledge, there has been no previous report of a CFD model of a neonatal airway with CNPAS. Here, we present the case of a patient with CNPAS and a neonate with normal nasal anatomy and perform descriptive CFD modeling of the nasal airway to assess the feasibility of using this method to characterize airflow in CNPAS patients.

Methods

Patients

This study fulfilled Nationwide Children's Hospital's institutional policy as case report ($n \leq 2$) and did not require IRB approval. Two neonates were enrolled in this study. One neonate was diagnosed with CNPAS which was managed without surgery, and the other was a neonate with no airway symptoms that had a CT scan done for non-airway reasons (Table 1, Figure 1). The CNPAS neonate did not receive anesthesia or sedation prior to her CT scan. The normal neonate was intubated and under general anesthesia when he received the CT scan.

The neonate with CNPAS was a pre-term twin female with mild bronchopulmonary dysplasia with apneas in the delivery room, admitted and with some improvement on nasal positive airway pressure and supplemental oxygenation. She had shallow breathing and periodic cyanosis. Noisy breathing with increased effort and desaturations and difficulty passing a 6 French catheter led to evaluation by the Pediatric Otolaryngology service. Examination revealed stertor and mild retractions, with nasolaryngoscopy demonstrating bilateral narrowed nasal passages, but a 2.2mm scope was able to be passed. Choanae, larynx and remaining structures were anatomically normal. CT scan findings are described in Table 1, confirming CNPAS with aperture width of 5.9mm and associated single solitary maxillary incisor. A subsequent brain MRI was normal. The patient was managed conservatively with topical decongestants and topical corticosteroid drops, transitioned from parenteral to oral nutrition, and discharged after 78 days of hospitalization.

The second patient was a full-term male with no nasal obstruction symptoms, and normal delivery and postnatal course. He presented to the Pediatric Otolaryngology clinic for evaluation of soft tissue anomaly of the nasal tip, for which a CT scan was performed.

Airway Model Construction

The CT scans enabled the construction of nasal airway models for each subject using methods described in detail previously and only briefly described here [14–17]. Realistic 3D models of the nasal airways were constructed using subjects' CT scan. The commercial software AMIRA (Visualization Sciences Group, Hillsboro, OR, USA) was applied to extract nasal cavity geometry. The segmentation was manually performed to extract the anatomy as accurately as possible. After necessary smoothing and correction for artifacts, a three-dimensional model of the nasal airway surface geometry was generated (Figure 2). Then the commercial grid generator ICEM CFD (Ansys, Inc., Canonsburg, PA, USA) was applied to generate a computational mesh of the nasal airway. Following our previous studies, a 4-layer prism mesh was adopted at the boundary with a total height of 0.2 mm near the mucosal surface to capture the rapidly changing near-wall air velocity [15, 18, 19]. The final nasal cavity meshes used for the simulation for the CNPAS patient and healthy control are 2.1 and 2.3 million, respectively.

Flow Simulation

The numerical simulation was performed using the commercial software package FLUENT 16.2 (Ansys, Inc., Canonsburg, PA, USA), by applying a physiologically realistic pressure drop of 15 Pascal (Pa) between the nostrils and the nasopharynx. This pressure drop of 15 Pa was chosen to simulate restfully breathing, a state that is most relevant to patients' symptoms during routine daily life. The selection of the pressure drop in the current study is for inhaling sufficient airflow for the CNPAS patient. It is an over-estimation for healthy newborns. To make a fair comparison, the same pressure drop is applied for both models. The flow rates for the CAPAS patient and healthy control are 0.62 and 4.67 L/min. Considering the volume flow rate for newborns is about 1.0 L/min, 15Pa can be a reasonable estimation for the CNPAS patient [20].

The laminar flow model in FLUENT is used in the current study. Although it is still an open question whether the nasal airflow during restful breathing is laminar or turbulent, our recent validation study has shown that the laminar flow model at low flow rate can provide a good approximation compared with Reynolds-averaged Navier-Stokes (RANS) turbulence models [21]. Along the nasal walls, the no-slip velocity condition was applied and the wall was assumed to be rigid. The numerical solutions of the continuity and momentum equations were determined using the finite-volume method. A second-order upwind scheme was used for discretization. The SIMPLE algorithm was used to link pressure and velocity. The discretized equations were then solved sequentially using a segregated solver. Convergence was obtained when the scaled residuals of continuity and momentum quantities were less than 10^{-5} .

Results

The geometric models and properties of the airways are shown in Figure 3 and Table 2, respectively. The normal airway had a 1.6-fold greater volume and 2.4-fold greater surface area than the CNPAS airway. The total resistance across the entire airway was approximately eight-fold greater in the CNPAS airway than the normal. The CNPAS neonate did weigh less than the normal neonate, which may partially account for the differences in volume, surface area, and total resistance. The anesthesia used for only the normal neonate may also have caused increased mucosal engorgement and affected the airway geometry.

The CNPAS airway had a lesser **bilateral** cross-sectional area and velocity than the control airway throughout the length of the model (Figures 4, 5). Therefore, the CNPAS airway had a lesser flow rate across the model. While there is a large pressure drop in the normal airway immediately after the entry point, the CNPAS airway has elevated pressures anteriorly and a pressure drop more posteriorly (Figure 4). The velocity was greatest in the CNPAS airway near the area of the pyriform aperture, where the cross-sectional area was least (Figure 5).

Discussion

CNPAS is a rare condition without consensus diagnostic criteria and treatment algorithms. Diagnosis is usually made by CT scan of the neonate with airway obstruction. Many reports on CNPAS have used PA width on imaging to diagnose the condition. Belden, et al.,

reported a PA width of < 11 mm to be diagnostic of CNPAS [2]. However, this criterion has been questioned as more recent case series have found most symptomatic patients have PA width much lower than 11 mm [5, 8, 22]. While most cases can be accurately diagnosed on the grounds of clinical suspicion along with imaging showing clear evidence of maxillary overgrowth, there is no consistent objective finding diagnostic of CNPAS.

The pyriform aperture width may play a role in the treatment algorithm for CNPAS as well. Surgery is generally only considered after failure of conservative therapy. One proposed treatment algorithm calls for a trial of conservative therapy prior to surgical correction for all patients for up to two weeks, regardless of PA width [23]. Previous studies, however, have attempted to identify those patients who are at highest risk of needing surgery. The case series reported by Wormald, et al., shows that a PA width of < 5.7 mm strongly predicts that surgical intervention will be required [5]. In contrast, Gonik and colleagues found no association between PA width and surgical intervention [9]. While the literature agrees on initially attempting conservative therapy for all patients, there is no recognized measure to identify those patients for whom conservative therapy is likely to fail.

The above represent some serious shortcomings of using PA widths measured on 2-dimensional imaging to guide diagnosis and treatment of CNPAS. This has been recognized in the literature. Multiple studies have attempted to use measurements other than the PA width to characterize the airway [8, 22]. Use of 3-D CT scans to characterize the airway has also been reported [24]. These tools may help better characterize the geometry of the CNPAS airway, but they still do not assess the geometry of the airway in its entirety or the flow dynamics across the airway.

The present study suggests that CFD may be another tool to assess the CNPAS airway. The 3-D models constructed in this paper demonstrate clear differences between the CNPAS and normal neonatal airway. The differences in airway geometry are not restricted to the area of the PA only, which is consistent with previous findings [22]. The simulation calculates flow parameters at various points along the airway which can be correlated to the local geometry (Figures 4, 5). Such data is very likely to be of consequence for surgical planning for these patients. Not only does CFD provide local details of flow within the nasal airway, it can also be used to calculate the resistance to flow across the entire nasal airway (Table 2). This numerical value may be used as an indicator to quantify overall severity of airway abnormalities, providing a novel approach to the diagnosis of CNPAS, risk stratification of patients, and assessment of response to surgical treatment. Older studies have used techniques such as plethysmography and rhinomanometry to quantify nasal airway resistance in infants [25, 26]. CFD is an improvement upon these techniques as it is non-invasive, does not require cooperation from the infant, and provides details of local airflow.

The use of CFD in a clinical setting for CNPAS patients certainly requires further research to correlate computational findings with clinical parameters in a larger sample. Normative data in neonatal nasal airways currently does not exist, and needs to be established. Potentially, functional assessment of obstruction may assist in predicting the clinical course of these children and alter or develop new treatment algorithms. The purpose of the present study is to illustrate the feasibility and potential benefits of CFD to analyze the neonatal

nasal airway. This is the first report of CFD being used to study neonates with CNPAS. Several groups have, however, used CFD to study the airways of children with obstructive sleep apnea [27–29]. There is more literature available on CFD in the adult airway. It has been used to study not only airflow, but also olfaction, drug delivery, and toxin exposure [30].

The greatest barriers to CFD use in the clinical environment are the time and cost associated with creating the model [31]. Modifications to the CFD techniques have been successfully made in the past to reduce the resources necessary to create models [15, 31]. Nonetheless, the procedure described in this study required 1–2 days per scan from an individual who is well-trained in the process. Because of the great interest in CFD and specifically in increasing its utility in the clinical setting, it is very likely that future research will identify modifications to the current techniques that reduce the complexity and resource requirement for generating models.

Conclusions

This study represents the first attempt to use CFD to model the airway of neonates with CNPAS. CFD modeling provides objective data related to the airway geometry and flow across the airway which may aid in diagnosis of CNPAS and treatment planning. Clinical use of CFD for this purpose requires further investigation of neonates with normal airways as well as neonates with CNPAS.

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Figure 1.
Axial and coronal CT images from the two patients studied: (a) CNPAS (b) normal airway control.

Figure 2. Schematic depicting the computational mesh of a nasal coronal section (left) and its corresponding CT scan image (right bottom). In a close-up view (right top), layers of small and fine elements along the wall can capture the rapid near wall changes of air velocity.

Figure 3.
Sagittal view of the 3D geometry overlaying with the CT scans for CNPAS patient (a) and normal control (b).

Figure 4.
Bilateral cross-sectional area (a), average cross-sectional velocity (b), and pressure (c) as a function of normalized distance to the nostril for CNPAS patient and healthy control.

Figure 5. Nasal airway of CNPAS patient (a) and normal control (b). 2D slide cuts are taken along the airway and color coded according to velocity magnitude.

Table 1

Summary of patient clinical data and CT findings.

	Sex	Gestation (weeks)	Age (days)	Weight (kg)	Imaging Modality	Imaging Indications	Findings
CNPAS neonate	F	31	63	3.0	non-contrast CT facial bones	Respiratory distress, narrowed nasal passages	PA 5.9 mm, solitary maxillary incisor
Normal neonate	M	39	37	3.9	non-contrast CT facial bones	Soft tissue anomaly of nasal tip	No airway or bony abnormality

Table 2

Geometric properties of each model from nostril to nasopharynx (see Figure 3).

	CNPAS	Normal
Volume (cm ³)	2.74	4.50
Surface Area (cm ²)	18.8	45.5
Total Resistance (Pa*s/ml)	1.46	0.193