Importance of Paranasal Sinuses in Computational Modeling of Nasal Airflow

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This paper investigates the importance of including paranasal sinuses in the computational modeling of the nasal airflow. Three dimensional models of human nasal airway with and without including paranasal sinuses were reconstructed from Computed tomography (CT) axial images of a subject with healthy nasal airway. The reconstruction process was performed using MIMICS® software program. The airway volume was discretized using TGRID® mesh generator. Steady Reynolds-Averaged Navier-Stokes (RANS) simulations were carried in both inspiratory and expiratory phases of respiratory cycle at a peak flow rate of 15 L/min in FLUENT®. The results show that the left and right nasal resistances change with less than 11% when paranasal sinuses are included in the computational model of the nasal airway. The flow into the sinuses is characterized by very low velocities during both inspiration and expiration conditions. The velocity distributions in the main nasal passage show small change predominantly in regions closer to the paranasal sinuses when compared to the model where sinuses were not included.

Nomenclature

CT = Computed Tomography
ΔP = Area weighted average static pressure drop between two faces
CFD = Computational Fluid Dynamics
LES = Large Eddy Simulation
τ = Turbulent Length Scale

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I. Introduction

Physiological flows through human body conduits such as the circulatory, respiratory and urinary tracts, has been a subject of research over the past few decades owing to their clinical significance and the interesting flow phenomena observed in these channels such as flow separation, flow recirculation regions or vortex shedding. However, the majority of these studies have been focused mainly in understanding cardiovascular flows \(^1\), since they account for majority of disease related deaths. Sleep apnea, where the human upper airway partially or completely collapses is also highly prevalent, in almost as 4 % of American population \(^2\) making it an equally important study. There were several clinical, experimental and computational studies on the human upper airway fluid dynamics \(^3\), but most of them were limited to retro-palatal, retro-glossal or the alveolar regions. There were relatively fewer studies focusing on the nasal cavity compared to the other airway regions, mostly due to the complex nasal airway anatomy. The focus of this study will be on the nasal cavity aerodynamics.

An average active person breaths about 7-14 liters of air each minute resulting in over 10000 liters of air per day, continuously exposing the epithelial surface of the lungs to the environment \(^8\). Adults when working or exercising can inhale up to 50 liters of air per minute. The exchange of gases in the lungs at the alveoli level requires a certain air quality. The temperature and humidity of the ambient air vary widely and often the air contains substances, droplets and particles, some of which are harmful to health. As an interface between the airway and the external world, the nose represents the primary defense system against the challenges of environment. The nose plays a major role in odor perception, filtration, heating, and humidification of the inhaled air. All the physiological functions of the nose are highly dependent on the nasal airflow, thus the knowledge of the flow characteristics through the nasal passages is therefore important \(^9\). Medically, the nasal passages are considered as an alternative route for drug delivery. The efficiency of drug delivery is related directly to the flow characteristics and the features of the delivery system used. An effective drug delivery with a precise deposition pattern may improve the response to the drug and potentially reduce the pharmaceutical dose.

Unobstructed nasal passages as well as sufficient contact of the air stream with the nasal epithelium are essential for the physiological function of the nose. Conditions which constrict the nasal airflow, i.e. nasal inflammation, nasal allergies, deviated septum, turbinate hypertrophy or polyps may have significant restrictions on nasal function as shown in several reviews and clinical studies \(^10\)-\(^12\). Among the most frequent afflictions that cause pathologic nasal obstruction are the common cold and allergic rhinitis. It is believed that about 10% of the population is affected by allergic rhinitis \(^10\). There is increasing evidence to support the idea that inflammation in the nasal passages whether caused by an irritant, allergy or common cold, causing blockage of the drainage sites of the sinuses, can lead to the development of a sinus infection. The prevalence of chronic sinusitis was estimated in 1997 at 14% of the overall population in the US \(^13\). Also, chronic rhinosinusitis was found in 25%-30% of allergic patients \(^14\). The pharmaceutical treatment of common cold or rhinitis may involve nasal drug delivery from devices such spray pumps, irrigations, or nebulizations. However, nasal deposition pattern of a drug depends upon a series of factors such as the initial flow conditions of the drug or the aerosol stream from the device (i.e. its velocity, swirling or no-swirling stream, droplet, and spray), the velocity of the inhaled airstream, the particle size, and the location in the nose where the drug is released.

Clinical studies in the nasal airway using tools such as acoustic pharyngometry cannot provide a complete understanding of the nasal cavity aerodynamics \(^15\). Subjective history and a careful CT scan study are only few options available for nasal airway diagnosis. Computational Fluid Dynamics (CFD) studies in nasal cavity henceforth, is much relevant to address this clinical limitation where a deeper insight in to the airflow characteristics, pressure drop relationships, particle deposition and even the ability to predict the surgical outcome with a virtual surgery is possible. In previously reported computational studies of nasal airways \(^16\)-\(^18\), paranasal sinuses and the lower airways were often not considered. The objective of this study is to evaluate the effect of paranasal sinuses on the flow characteristics in the nasal airway using a computational simulation on an anatomically accurate nasal cavity model.

A. The Anatomy of the Nasal Airway

The nasal cavity is separated into left and right nasal regions by a nasal septum with nose on its anterior side and extending continuously into pharynx on the posterior. The floor of the nasal airway rests on the roof of the mouth, the hard palate. It consists of bone and cartilage forming airway passages called meatus. The horizontal outgrowths on the sides of the nasal cavity are called turbinate or conchea. The nasal cavity lined with a mucous substance humidifies inspired air and also filters out any particles before air reaches lungs \(^10\). It opens into different paranasal sinuses (ethmoidal, sphenoid, maxillary and frontal) which under normal conditions are hollow air-filled cavities with scanty amounts of mucous lining, through small conduits called ostia. During common cold, sinusitis or during
other inflammatory diseases, sinuses are filled with mucous drain from its lining and if the ostises are blocked, the secretion cannot escape into nasal cavity thereby building pressure in the nasal cavity. Figure 1, 2(c) and 2(d) show different parts of the nasal anatomy.

![Nasal cavity Anatomy – CT Coronal Image](image_url)

**Figure 1.** Nasal cavity Anatomy – CT Coronal Image

### II. Methodology and Case Formulation

#### A. CT Data

Axial series of Computed Tomography (CT) scans were acquired for a 17 year old female patient with no known nasal airway disorders on a GE Medical CT Scanner. The image resolution was 512 X 512 pixels and the slice gap between two successive axial images was 2.5 mm. An example of CT axial scan is shown in Figure 2(a). Twenty such scans spanning entire nasal cavity and containing three of the four paranasal sinuses (i.e. maxillary, sphenoid and ethmoidal sinuses) are considered for this study. Axial images containing the frontal sinuses were not available with this patient scan; hence frontal sinuses were not included in this analysis. It is expected that, this exclusion of frontal sinuses, which are anatomically much above the level of nasal cavity and right behind the forehead may not significantly affect the flow dynamics for the flow rates considered here. Also, sometimes frontal sinuses do not develop at all after birth in few individuals.

#### B. 3D Model Reconstruction

Patient specific three dimensional (3D) nasal airway models were reconstructed from the axial series scans using medical imaging software, MIMICS® (Materialise, Belgium). For this study two 3D models (Model 1, Model 2) were reconstructed as shown in Figure 2(c) and 2(d) respectively.
Model 1 contains the nasal airway including the paranasal sinuses and Model 2 is the reconstructed nasal cavity excluding paranasal sinuses. To obtain these 3D models, the airway contours are identified in each of the axial scan as shown in Figure 2 (b) based on image threshold, with black regions of the scan identified as feasible air-filled regions. To reconstruct Model 2, the paranasal sinus regions in each scan are manually erased to obtain airway contours under the supervision of a physician. A surface is skinned on all these identified airway contours to obtain 3D Surface models. These 3D models were then smoothed and re-meshed to obtain a better triangulated surface mesh. The inlet, outlet and wall faces were demarcated before exporting the surface meshes into meshing software, TGRID® (Fluent Inc., Lebanon, USA). TGRID discretizes the nasal airway volume with unstructured tri/tetrahedral volume elements.

A fine, a medium and a coarser grid with different grid spatial resolutions were made for both Model 1 (0.32, 0.6 & 0.96 million cells respectively) and Model 2 (0.33, 0.7, 1.03 million cells respectively) to perform a grid sensitivity study. All the generated meshes are shown in Figure 3 for Models 1 and 2. The number of cells was chosen so as to have the equivalent cell edge length based on the maximum volume of the tri/tetrahedral cell as the same order as the turbulent length scale. The three different grid resolutions have different maximum cell edge lengths. The turbulent length scale ($\tau$) is defined as 0.07 times the equivalent diameter based on the minimum cross-sectional area of the nasal airway.
C. Flow solver and Boundary Conditions

The commercial CFD solver Fluent 6.3 (Fluent Inc., Lebanon, USA) is used to solve the flow governing equations with appropriate boundary conditions (BC). The incompressible flow is predicted using the steady RANS approach with the standard k-ω turbulence closure. Inspiration and expiration phases of the airflow are considered at the flow rate of 15 L/min. Convergence criteria is given by a maximum residual error of 10e-4. The boundary conditions were defined as velocity inlet at the inferior part of the nasopharynx and outflow BC at the nostril exits during expiration and velocity inlet at the nostril ends and outflow at the inferior end of the nasopharynx during inspiration. The velocities and the outflow conditions were area weighted at the nostril exit during inspiration and expiration respectively. The wall no-slip boundary conditions for velocity were imposed. Second order finite volume upwind schemes were chosen for solving the discretized momentum and turbulent transport equations. The coupling between the velocity and pressure fields was realized through the SIMPLE algorithm. The material property was chosen as air with a density of 1.225 Kg/m3 and a viscosity of 1.79e-5 kg/m-s. A turbulent intensity of 10% and a turbulent length scale (τ) of 0.001m were considered.

D. Plane Definitions for data analysis

For better visualization and for an easier interpretation of the data, thirteen planes (Planes 1-13) were generated through the complex geometries of the Models 1 and 2 as depicted in the Figure 4. Planes 12 and 13 correspond to the right and left nostril respectively. Plane 1 corresponds to the inferior end of the nasopharynx. Plane 5-10 are coronal planes created 5mm apart. Planes 3, 4, 10, 11 are made normal to the curvature of the geometry. Plane 2 is parallel to plane 1 and 6mm apart. Besides these planes, a mid- longitudinal (mid-sagittal) plane is also generated.
III. Results and Discussion

A grid sensitivity study was carried out on both models 1 and 2 with three different mesh resolutions during a peak inspiratory and expiratory flow rate of 15 L/min. Figure 5 shows the area-weighted average static pressure drop between each of the planes shown in Figure 4 with respect to Plane 1.

Figure 5. Grid Sensitivity Study: ΔP between each of Planes 1-13 with respect to Plane 1 on three different grid resolutions for both inspiration and expiration phases at a peak flow rate of 15 L/min on both models 1 (with sinuses) and 2 (without sinuses).
It is observed that pressure drops for medium and fine grid resolutions are in very good agreement. Similar agreement is observed for maximum velocity in these planes (not shown) between fine and medium grids resolutions. Since, the computational load and time were reasonable for a finer mesh, the results hereafter are presented only with a finer grid resolution for analysis.

Table 1, shows the pressure drop ($\Delta P$) between the inferior nasopharynx plane (Plane 1) and each of the left and right nostril planes (Plane 12, Plane 13 respectively) during peak inspiratory and expiratory flow rates of 15 L/min in both models 1 & 2. Including paranasal sinuses in Model 2 changed the overall flow resistances in the left and right nasal cavities by less than 11%. Flow resistances are defined as the pressure drop for every 1L/min of volumetric flow rate.

<table>
<thead>
<tr>
<th></th>
<th>Left Nasal Pressure drop (Pa)</th>
<th>Right Nasal Pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expiration</td>
<td>Inspiration</td>
</tr>
<tr>
<td>Model 1 (with sinuses)</td>
<td>10.936</td>
<td>11.162</td>
</tr>
<tr>
<td>Model 2 (without sinuses)</td>
<td>12.1885</td>
<td>12.122</td>
</tr>
</tbody>
</table>

Table 1. Absolute $\Delta P$ in left and right nasal cavities during a peak flow rate of 15 L/min

Figure 6 shows the contours of mean velocity magnitude across thirteen planes as defined in Figure 4 for Models 1 & 2 at an inspiratory flow rate of 15 L/min. The highest flow velocity in the nasal airflow was found to be 3.58 m/s in the region downstream of the nostrils, whether paranasal sinuses were included or not. This is due to the fact that this particular location corresponds to the low cross sectional area of the nasal cavity termed as the nasal vestibule or nasal valve which creates a large flow resistance during inspiration.

Figure 6. Contours of Velocity Magnitude (m/s) during an inspiratory flow rate of 15 L/min at selected cross sectional planes along the nasal airway Model 1(with sinuses) and 2(without sinuses).
The maximum velocity is observed in the left nasal cavity compared to the right nasal cavity as the latter is slightly wider. Relatively higher flow velocities were observed in the middle airway and middle meatus followed by the inferior airway closer to the nasal airway bed in this patient specific model.

Figure 7 shows the mean velocity magnitude flow distributions during inspiration in planes 4, 5, 6, 8 (see also Figure 4). Including paranasal sinuses in Model 2 as compared to Model 1, changed the flow velocity distribution locally and this can be predominantly observed in the planes containing the maxillary and ethmoidal sinuses. Flow velocities in the maxillary sinuses are extremely small during inspiration. Similar observations are seen during expiratory phase for the same flow rate but with even weaker secondary flow structures in sinuses.

Figure 7. Contour of Velocity Magnitude (m/s) during inspiratory peak flow rate of 15 L/min at selected planes for Models 1 and 2 (detailed view)

Figure 8 shows the contours of velocity magnitude in mid-sagittal plane for Model 2 during inspiration. Small recirculation regions were observed as expected during inspiration and expiration along the posterior wall of the nasopharynx in the region proximal to Plane 4 where the left and right nasal passages merge towards the nasopharynx and the flow changes its direction by almost 90 degrees. During inspiration, very little air enters the sphenoid sinuses, located posterior to the nasal airway and secondary vortex of low velocities were observed as shown in the zoomed view of velocity vector plot. During expiration, these secondary flow structures in the sphenoid sinuses are much weaker.
IV. Conclusions and Future Work

In this paper, the importance of paranasal sinuses in the computational modeling of nasal airflow was studied. Two numerical nasal airway models, one including paranasal sinuses and other excluding were reconstructed from CT imaging data acquired in a female adolescent patient with a healthy nasal airway. The function of paranasal sinuses was not completely understood till today. Most of the computational studies, previously reported on the nasal airflow do not include the paranasal sinuses owing to its complex anatomy and the resultant flow fields. The principal objective of this study is to see if the flow distribution will be altered by the presence of these paranasal sinuses in the computational modeling.

During inspiration and expiration, the local flow distribution in the regions proximal to the planes containing the sinuses slightly changed. This was more significant during inspiration compared to the expiration. Regardless of the respiratory phase (inspiration or expiration), including sinuses in the computational modeling changed nasal resistances by less than 11%.

Minimal flow exchange into sinuses is observed in Model 2 during both inspiratory and expiratory simulations. In maxillary sinuses, secondary flow with small velocities was noticed. Flow separation on the posterior wall of nasal cavity where left and right nasal cavities merge into nasopharynx was also observed as previously reported\(^{19}\).

The superiority of Large Eddy Simulation (LES) as compared with steady RANS models to predict transitional/turbulent flow situations, high streamlined curvature flows, flows where separation occurs is well known\(^{20}\). Future studies will be performed at higher flow rates (the present situation considers normal breathing) by using LES to observe the nasal airflow dynamics.

Some of the assumptions used in the present simulations are discussed in the following paragraph. The mucosal walls of the sinuses contribute to humidification and the temperatures in the sinuses are maintained between 31 and 37 °C \(^{21}\). In this study, it is not accounted for these effects. Another simplification is that the airway model is assumed to be rigid. In reality, some of the internal nasal structures are deformable continuously with respiratory cycle. At higher flow rates during inspiration, the external walls just downstream of nares may collapse. An important assumption considered here is that of steady (i.e. continuous) flow simulations associated with this study. A more elaborate understanding of the actual flow dynamics can be observed in the transient simulations taking the...
respiratory cycle into account. Also, we acknowledge that this study includes only a single patient specific model and the anatomical features vary individually. Although CFD can predict the pressure drops, flow and particle distribution in nasal airway, these features have to be correlated with the clinical data to completely understand the physiological function.

The current study is an effort to use CFD as a non-invasive tool to better understand airflow characteristics in nasal airway. Inclusion of paranasal sinuses in the computational modeling of the nasal airflow was observed to not significantly affect the flow resistances in the left and nasal cavities, although local flow velocity distribution was found to change in regions proximal to the sinuses. Secondary flows of small velocities are observed in the paranasal sinuses. Considering the limitations and assumptions in this study, future studies are required to completely understand the role of paranasal sinuses in finer detail.

**Acknowledgments**

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**References**