Airflow Simulation inside the Nasal Cavity

Milad Ahmadia,*, Mohammad Zuberb, S.M. Abdul Khaderc

a Department of Mechanics of Solids, Surfaces and Systems, Faculty of Engineering Technology, University of Twente, Netherlands
b Department of Aeronautical & Automobile Engineering, Manipal Institute of Technology, India
c Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, India

Abstract

Filtration of particulate matters in the human nose depends on the individual aspects of the nasal cavity such as the geometry and flow rate collectively. To better understand the physiology of the nose, a 3D computational model of a human nasal cavity was developed based on the computed tomography (CT) scans of a healthy female. Also, the airflow and distribution patterns were investigated and compared for two different flow rates: 7.5 and 15 L/min. COMSOL Multiphysics was used to analyze the velocity patterns for laminar flow rates of 7.5L/min and 15L/min and the differences were explored and analyzed.

1. Introduction

One main part of the respiratory system is the nasal cavity which performs a variety of physiological functions. It is responsible for heating and humidifying inhaled air while filtering the air pollutants and toxic particles that may enter the airway. Additionally, the nasal cavity provides an alternative pathway for drug delivery [1].

In this regard, detailed air-flow patterns can provide information that is pertinent to the prediction of gas-particle flows and regional tissue exposure to inhaled air. The numerical data which can produce highly quantitative results ideally complements existing experimental data that often lack fine details.

With the growth of science and the emergence of new technologies, new branches in medical engineering have been created. The application of engineering sciences in medicine and patient health has increased and technology has helped human health. Diagnosis of various diseases such as cancer, blood diseases, digestive problems, etc is done by new methods and devices, and in the meantime, simulation and the use of imaging [2, 3] have spread a lot.

Recent developments in medical imaging (MRI and CT scanning) coupled with computational science have opened new possibilities for physically realistic numerical simulations of nasal airflow [4-6].

The main factors that contribute to the airflow patterns are the nasal cavity geometry and the flow rate. For a realistic human nasal cavity, the left and right sides of the nasal cavity differ geometrically while nasal morphological differences can be found between individuals. The inspiratory flow rates for adults can range between 5L/min and 12L/min for light breathing and 12–40L/min for non-normal conditions such as during exertion and physical exercise. Usually breathing switches from pure nasal flow to oral-nasal flow at this higher range. Additionally, flow rates for extreme forced inhalation conditions have been found to reach 150L/min [7].

Inter-subject variations in nasal anatomy will cause variations in nasal flow patterns, which is a concern when trying to use the results of a single model. Thus, this CFD study presents flow patterns for laminar steady flow for flow rates of 7.5 L/min and 15 L/min. CFD methods are beneficial in its ability to provide comprehensive data that are normally difficult to produce through experiments due to intervention and clinical risks for the involved participants. The flow in

* Corresponding author: milad.ahmadi66@gmail.com

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the vestibule, nasal valve, turbinate, and nasopharynx regions was studied in detail and the variations in flow patterns and flow features such as velocity and flow distribution are also presented.

2. Methodology and Governing Equation

The anatomical model of a 39-year-old Malaysian subject having normal nasal airway was obtained from CT scan images sourced from Universiti Sains Malaysia Medical Campus Hospital. The nasal anatomy was attested to be normal by the ear, nose, and throat (ENT) surgeon. As it can be seen in Figure 1 [8], the scans produced a total of 385 slices of axial, coronal, and sagittal images which accounted for the complete nasal cavity area, from nostril to nasopharynx. The increment between each slice of the scan images is 0.8mm and the scan pixel resolution is 0.434mm. The scan images were segmented slice by slice with an appropriate threshold value using Mimics.

![Figure 1. CT scan images and 3D model of human nasal cavity](image_url)

The 3D polyline data of the nasal cavity is then edited in CATIA and meshed using hybrid mesh generated using Tgrid and GAMBIT. The hybrid mesh consisted of a combination of 6 layers of prism cells near the near-wall boundary with a wall γ+ maintained equal to 1 and the tetrahedral elements at the remaining flow domain. The numerical simulation was performed using the commercial CFD solver COMSOL Multiphysics. The simulation was carried out on an Intel (R) Core (TM) i5-5200U CPU @ 2.20GHz, 2 cores, which required approximately 3 days of runtime for the entire simulation.

As can be seen in Figure 2, the boundary conditions that were used are as follows: a rigid nasal wall was assumed and the simulation ignored the presence of mucus. A no-slip boundary condition was defined at the nasal wall and the inspiration mechanism was defined using mass flow inlet boundary at the nostril inlet. At the outlet, outflow boundary condition was used. Steady-state laminar airflow rates of 7.5 and 15 L/min were modeled. This was in general agreement with previous researchers [1, 8-10] who determined the laminar nature of the flow, for flow less than 15 L/min.

Comparison and validation were carried out using the analysis of the models with previous researches [5, 6, 8, 10-13].

The airflow simulation was based on the Navier-Stokes equations [13] for the continuity equation 1:

\[
\frac{\partial u_i}{\partial x_i} = 0
\]  

(1)

And conservation of momentum, equation 2:

\[
u_i \frac{\partial u_i}{\partial x_i} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left( (\nu + v_t) \frac{\partial u_i}{\partial x_i} \right)
\]  

(2)

Where \( u_i \) is the air velocity in three Cartesian coordinate directions, i.e., \( i = 1, 2, \) and 3, \( p \) is the pressure, \( \rho \) is the fluid density, \( \nu \) is the air kinematic viscosity and \( v_t \) is the kinematic turbulent (eddy) viscosity. The eddy viscosity is computed...
with the use of a turbulence model. The airflow was assumed to be incompressible and steady. The "Turbulent Flow, SST" RANS model, was used to simulate the flow.

Figure 2. Volume mesh of nasal cavity and its different regions

Velocity fields. This model has been found to provide very good calculations of wall-bounded flows even with highly separated regions. The SST combines the advantages of both the \( k-\varepsilon \) and \( k-\omega \) methods. The \( k-\varepsilon \) turbulence model has a near-wall treatment allowing accumulation of nodes towards the wall without any special non-linear damping function, whereas the \( k-\omega \) turbulence model is more accurate for flows involving strong streamlines curvature. The constant parameters for turbulence model in this study are: \( a_1 = 0.31 \), \( \beta_1 = 0.075 \), \( \beta_2 = 0.0828 \), \( \sigma_{\omega 1} = 0.5 \), \( \sigma_{\omega 2} = 0.856 \), \( \sigma_{k1} = 0.85 \), \( \sigma_{k2} = 1 \), \( K_v = 0.41 \), and \( B = 5.2 \). In this study, there are about 90000 tetrahedral type mesh and around 50000 triangular type mesh.

3. Results and Discussion

Airflow contours in the nasal cavity provided qualitative visualization of the flow fields in the nasal model. The differences between the 7.5 and 15 L/min flow rates are shown by the 3-D presentation of the contours in Figure 3. The main inhaled flow path travels through almost the entire nasal cavity and downward toward the lungs eventually. The distribution of the flow is also dominant in the lower part of the nasal cavity. At the nasopharynx, the left and right cavities merge, which led to the flow mix more intense in this region. Then the airflow accelerated through the nasopharynx due to the narrower cross-sectional area of the pharyngeal airway.
Figure 3. Velocity contours for inhalation rates of 7.5 & 15 L/min

Figure 4 shows the air velocity magnitude in different regions of the nasal cavity. As can be seen below, the Nasopharynx section has the highest value for the velocity field while this value is the lowest for the middle-turbinate region which is understandable due to the wider cross-section area of this region. The velocity values are 1.4 and 2.8 m/s for flow rates of 7.5 and 15 L/min respectively. In the middle plane section, the flow is directed downwards with the bulk flow concentrated in the upper and lower region close to the septum walls.

Figure 4. Velocity comparison inside the nasal cavity
4. Conclusions

Filtration of particulate matters in the human nose depends on the individual aspects of the nasal cavity such as the geometry and flow rate collectively. To better understand the physiology of the nose, a 3D computational model of a human nasal cavity was developed based on the computed tomography (CT) scans of a healthy female. Also, the airflow and distribution patterns were investigated and compared for two different flow rates: 7.5 and 15 L/min. COMSOL Multiphysics was used to analyze the velocity patterns for laminar flow rates of 7.5L/min and 15L/min and the differences were explored and analyzed.

References


