Study on Nasal Deposition of Micro Particles and Its Relationship to Airflow Structure

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Abstract: A computational model was established in order to study the pressure, velocity and particle deposition in a human nasal cavity, including: nasopharynx, main airway, nasal valve and vestibule. Coronal CT scan images of a 39 years old Malaysian female were used to produce the 3D model. The Lagrangian approach was used to find the trajectories of micro-particles for 20 L/min flow rate. The deposition rate of micro particles were evaluated and the major hot spots for the deposition of injected particles were found. On the other hand, the pressure drop and velocity magnitude of the patient were investigated and compared in this paper. It was found that the particle diameter has significant impact on deposition patterns for the micro particles. Additionally, with increase of particle diameter, micron particles experienced higher total deposition efficiency.

Keywords: Micro particle; Nasal airway; Deposition pattern; CFD

I. INTRODUCTION

Moisturizing and keeping clean the air that moves through the nose and get into the lungs are the core responsibilities of the turbinates in human body and respiratory system. In certain situations, inflammatory reaction of turbinate is the first sign that they come across an allergenic substance which can lead to inflammation of them but in real life having such turbinate is not quite as harmful as it sounds. To solve this problematic issue, there are a few actions that can be taken. Turbinates are bony projections which can be found on both sides of the nasal cavity. There are typically three sets of them: the inferior turbinate, which is the largest and is located closest to the nostril, the middle turbinate which is the second largest and the superior turbinate which is the smallest in size amongst
three of them [1]. One of the processes which is totally normal and goes unnoticed by majority of people, is the filtration process of impurities such as particles and dust which is done by tubinates and it usually occurs about twice a day, by expanding and contracting repeatedly: once on the right and once on the left side. Inflamed turbinates are result of entering external substances such as tree pollen which can caused allergic response in a body, in which, it treats them as external intruders and targeted individual can experience respiratory problems [2].

Therefore, the deposition of inhaled particles such as dust, microorganisms, photo chemical smog and other irritants in the air way passages is a serious health concern. These aerosols and particles can be released from different sources include diesel exhaust in the range from 5 to 500 nm [3], cigarettes smoke (140–500 nm) [4-5] and radio-active decay (1–200 nm) [6]. Latest studies have validated that micro-sized particles are less harmful and dangerous when compared with fine and especially ultra-fine particles of the same material and respiratory diseases such as lung cancer can be result of these ultra-fine particles [7-11]. Investigations have shown that, all particles smaller than 10 μm in diameter are biologically active and could cause allergic responses and in some case also lead to cancer in vulnerable persons [1-2]. Moreover some of these aerosols which are biological in nature, such as severe acute respiratory syndrome and avian flu, usually range (20-200 nm) [12]. Another major area where the study of particle deposition can be of much use is the drug delivery system, wherein it is desired to deposit some particles in the affected nasal cavity sections. Hence, estimating the dissemination of deposited particles in different areas of the human nasal cavity can be considered as significant interest not only to compute what amount reaches the lung, but also to calculate the dosage to upper air ways for both therapeutic effectiveness of inhaled particles and health risk management.

Deposition rate of particles in oral airway and also structure of air flow were investigated numerically by many researchers, mostly using a simplified model of the oral airway [13-14]. But in recent analysis conducted by Jayaraju et al. [15] and Tavakkoli et al. [16], a realistic geometry of human oral airway was used and results of their numerical study for the flow field and particle deposition related to nasal model was presented. In another recent investigation by Xi et al. [17], MRI head image of a 6-year-old boy was used in order to analyze the deposition and transport of respiratory aerosols in a nasal–laryngeal air way model. The localized and sub-regional deposition values could be used in identifying the site of main likelihood for respiratory lesions. It is very vital to identify these hot spots for particles deposition in which as the cancer formation is more possible. As a result, the information of local deposition can be valuable in health risk assessment, because a high local dose may lead to tissue damages or can be first cause of a disease process [18], while the average dose is still in the acceptable range. Besides, [19] carried out numerical study of the respiratory flow pattern in a realistic human upper airway using the CT images of a healthy volunteer. In another study, they utilized the state of art hybrid mesh scheme to generate requisite mesh for the nasal model [20]. Multiple magnetic resonance imaging (MRI) axial scans are used by Mylavaram et al. [21] to create and develop an anatomically precise human upper airway model. The main objective of this paper is to carry
out the numerical investigation of human nasal cavity and also analyze the effects of turbinate on airflow behavior. Moreover, study on micro aerosol deposition in nasal cavity is another key purpose of this paper.

II. METHODOLOGY

This section presents the method used to evaluate the particle tracks in the nasal cavity model developed. It also describes the step by step methods in order to achieve the final results for contours and pressure drops comparison. Reconstruction of 3D anatomical model of the human nasal cavity can be very time consuming. The 3D anatomical model is created by using CT scan data of human nasal cavity, in which 2D CT scan images are converted into 3D CAD data. For this purpose the medical image processing software, MIMICS is employed and in final stage CATIA which is a CAD software is employed to construct the surface geometry. In this study, the nasal airway constructed from CT scan images of a healthy 39 years old Malaysian female. The image of the nasal airway was taken from pre-existing CT scan data which was available in Medical Campus Hospital of Universiti Sains Malaysia. The nasal anatomy was proved to be normal by the ear, nose and throat (ENT).

As mentioned before, in this study the MIMIC software used, MIMIC has the ability to generate and display the 3D anatomical model of the nasal cavity from the segmented scan images. MIMICS also provide the export function which can be used to export the 3D object produced from the segmented CT scan images into IGES file and can be directly used in any CAD system. Then the next step, is using the CAD software. The coordinates of the contour point extracted from the CT scan data of the human nasal cavity was imported into CAD software package, CATIA using Digitized Shape Editor (DSE) workbench for surface model generation. After using this software and its editorial capability, final 3D model of the nasal cavity attained from CATIA which can be used for computational modeling. Afterwards GAMBIT software was used in order to convert the surface of nasal model into detectable faces using STEP (*.stp) file format.3D model of nasal cavity including paranasal sinuses was established and developed in a real way. Both nasal cavity and sinuses coronal cross sections for developing pre and postoperative model of nasal airway were used which were derived from CT scan images of an adult male. The distance between Coronal cross sections were 1 mm and CT scan resolution was 512 × 512 pixels. The scans captured outlined slices in the \(X-Y\) plane at different positions along the \(Z\)-axis from the entrance of the nasal cavity to just anterior of the larynx depending on the complexity of the anatomy. Three dimensional modelling program named GAMBIT (ANSYS Inc., USA) was used in order to import the scans of coronal sections and link the available points on the coronal sections to form smooth curves. A preliminary model with 349148 nodes and total amount of 1691940 body elements was constructed. The model included three components namely: inlet, wall and outlet as show in figure 1 [20].
An implicit pressure based used for simulation and SIMPLE pressure-velocity coupling was applied for the second-order run. For higher precision purpose, a second-order scheme utilized. The values of temperature, viscosity and density in the simulation were consistent with the atmospheric conditions.

In this paper, only steady flow rate of 20 L/min is considered and validated accordingly with work of Wen et al. [8]. The outflow boundary condition was defined at the nasopharyngeal exit with zero diffusion flux for all flow variables in the direction normal to the exit plane because the values of flow velocity and pressure were unknown prior to the solution of the flow problem. A one-way coupling assumption for particle transport was employed, which means the effect of particles on the airflow was ignored. Afterwards, the air flow was simulated in the first place and then the trajectories of each particle were calculated. Lagrangian approach was used in order to study the deposition and motion of micro particles. In micro particles, inertia has significant impact on their motion and this behavior make Lagrangian model as an appropriate choice. Particles were injected uniformly from nostril in nasal model.

The governing equations for the airflow are continuity and balance of momentum are as below [22]:

\[
\nabla \cdot \vec{u} = 0
\]

\[
\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{u}
\]

In Equations (1) and (2), \( \vec{u} \) is the velocity vector, \( t \) is the time, \( P \) is the fluid pressure, \( \rho \) is the constant fluid density, and \( \nu \) is the kinematical viscosity. Lagrangian method was used in order to calculate deposition and transport of micro particles [22]:
\[ \frac{d\mathbf{u}_p}{dt} = \frac{3\mu C_D R_p}{4\rho_p \rho} (\mathbf{u}_p - \mathbf{u}) + g \]  

(3)

In Equation (3), \( \mathbf{u}_p \) is the particle velocity vector, \( \rho_p \) is the particle density, \( \mu \) is the fluid viscosity, \( g \) is the acceleration gravity, and \( \text{Rep} \) is the particle Reynolds number. In the equation, \( C_D \) is particle drag coefficient

\[ C_D = \frac{24}{\text{Re}_p} (1 + 0.15 \text{Re}_p^{0.687}) \]  

(4)

And \( C_{\text{slip}} \), which is Cunningham slip correction factor defined as:

\[ C_{\text{slip}} = 1 + \frac{2\lambda}{d_p} [1.257 + 0.4 \exp(-1.1 \frac{2\lambda}{d_p})] \]  

(5)

Where \( \lambda \) is the air mean free path.

III. RESULTS & DISCUSSION

A. Air Flow Structure

In present paper, the analysis and investigation on air flow fields for flowrate of 20 L/min were conducted. As discussed earlier, turbulent airflow regime was chosen for the targeted flow rate. Figure 2 depicts the velocity contours for flow rate of 20L/min at two different viewpoints in the nasal cavity model. As it can be seen in the schematic, the air enters the nasal model uniformly from the nostril up to nasopharynx passing through 10 different sections of the model.

As depicted below in figure 2, for the velocity contours, vestibule (section after nostril) and nasopharynx sections experienced the highest values in the nasal model; which this value is much higher at nasopharynx section because this section has the minimum flow area which is almost one-third of the area at vestibule section. It also can be seen the model experienced the lowest values in midsection of main airway and nasal valve respectively.
Figure 2. Contours of velocity (m/s) for 20 L/min flow rate.

B. Pressure Comparison

Figure 3 illustrate the pressure contours for 20L/min. The pressure contours from nostril (inlet) up to nasopharynx (outlet) are analyzed and shown. As it is shown in the figure, the model experienced the highest value at the nostril, vestibule and outlet sections, especially at inlet area, while the pressure follows a stable and steady trend for the main airway and nasal valve section and there no significant change in pressure for these sections.

Figure 3. Contours of pressure (pascal) for 20 L/min flow rate.
The simulations for pressure were performed for breathing rates of 5, 10 and 20 and 50 L/min for nasal cavity model. As it can be seen in, different flow rates with their corresponding pressure drop values are shown and compared.

As it can be seen in the table I, with increase of the flow rate in nasal model, the pressure value increases accordingly. Moreover, the pressure drop in turbulent regime is more obvious than pressure drop in the laminar regime, while as illustrated below there is a noticeable rise from flow rate of 20 L/min to 50 L/min, in which, the discrepancy is around 100 pascal. Obtained Results show a good agreement with the previous research work related to pressure drop at various flowrates [22].

<table>
<thead>
<tr>
<th>Flow Rate (L/min)</th>
<th>Pressure (Pa.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.82</td>
</tr>
<tr>
<td>10</td>
<td>16.90</td>
</tr>
<tr>
<td>20</td>
<td>59.80</td>
</tr>
<tr>
<td>50</td>
<td>154.27</td>
</tr>
</tbody>
</table>

C. Particle Deposition

Figure 4, illustrate the velocity streamlines for particle size of 15 μm for breath rate of 20L/min. As it can be seen in the figure, the velocity of particles decrease at they pass through the vestibule and reach the main airway region, it follows a constant flow pattern until it reach the nasopharynx which it experienced the peak value for the particle velocity. Furthermore, as it can be seen in figure 4, a noticeable portion of particles pass through the main airway along with recirculation type of motion in the upper side of main airway which referred as olfactory region. Moreover, the intensity of the particle streamlines is higher in right side section of the nasal model which is illustrated in top view on the right side of the figure.
Figure 5 represents the results for three different particle sizes which are $5 \, \mu m$, $10 \, \mu m$ and $15 \, \mu m$ subject to airflow rate of 20 L/min. Particle deposition can be expressed as inertial parameter (IP) which is related to deposition of the particles. It is defined as IP = $d^2 \, Q_a$ where $d$ stands for particle aerodynamic diameter and $Q_a$ is the volumetric airflow rate. The other important factor in particle deposition is its efficiency which is referred as the ratio of total number of particles trapped on the targeted surfaces, which in this paper, are vestibule, nasal valve, main airway and nasopharynx, over the total number of particles released at the inlet (nostril).

As shown in figure 5, the regional deposition fraction is highest in the vestibule and nasal valve sections and they can be considered as hot spot areas while the nasopharynx experienced the least particle deposition. As it can be seen in the figure, for $15 \, \mu m$ case, the highest deposition fraction is for vestibule which is around 60%, while in other two diameter sizes ($5\mu m$ and $10\mu m$) this peak value is for nasal valve region and equal to 7% and 42% respectively. This has implication in drug delivery studies. This study proves that vestibule and nasal valve are regions of major deposition. Thus, in order to achieve better drug delivery concept, the particles should be able bypass the vestibule and the nasal valve bottlenecks. This can ensure the deposition of particles on the turbinates and other posterior regions of the nose.

Furthermore, it can also be inferred that human nose is an excellent filtering device which restrict hazardous particles reaching the sensitive turbinates. Additionally it’s is shown that with increase in diameter of the particles, the deposition rate also increase and the discrepancy of the rates between each section is more obvious.
IV. CONCLUSION

Air flow structure for flow rate of 20 L/min was used and its behavior within different sections of nasal model was simulated and hot spots were presented accordingly. Moreover, a detailed pressure drop comparison was conducted for flow rates of 5 to 50 L/min and achieved results were analyzed and described in related section. Additionally, a comparative study of micro particles deposition by aim of Lagrangian approach was conducted. For micro particles, the impact of different factors that are applicable to micro particles were discussed and the detailed local deposition patterns were presented. According to presented results in this paper, particle diameter has significant influence on deposition patterns and increase the size of diameter leads to higher deposition efficiency in nasal model. The findings which demonstrated in figure 5 show a good agreement with recent published studies about numerical analysis of micro particles [16].

Lastly, the present study further clarifies the power and capability of CFD techniques for predicting the airflow and particle deposition patterns in nasal passages. It is essential to emphasize that for real breathing, both the airflow rate and the flow direction change constantly and the corresponding micro deposition rate might be different from the results presented in this study.

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