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Numerical simulation of airflow and micro-particle deposition in human nasal airway pre- and post-virtual sphenoidotomy surgery

Hojat Bahmanzadeh [a], Omid Abouali [a,*], Mohammad Faramarzi [b], Goodarz Ahmadi [c]

[a] School of Mechanical Engineering, Shiraz University, Shiraz, Iran
[b] Department of Otolaryngology Head & Neck Surgery, Shiraz University of Medical Sciences, Shiraz, Iran
[c] Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY, USA

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ABSTRACT

In the present study, the effects of endoscopic sphenoidotomy surgery on the flow patterns and deposition of micro-particles in the human nasal airway and sphenoid sinus were investigated. A realistic model of a human nasal passage including nasal cavity and paranasal sinuses was constructed using a series of CT scan images of a healthy subject. Then, a virtual sphenoidotomy by endoscopic sinus surgery was performed in the left nasal passage and sphenoid sinus. Transient airflow patterns pre- and post-surgery during a full breathing cycle (inhalation and exhalation) were simulated numerically under cyclic flow condition. The Lagrangian approach was used for evaluating the transport and deposition of inhaled micro-particles. An unsteady particle tracking was performed for the inhalation phase of the breathing cycle for the case that particles were continuously entering into the nasal airway. The total deposition pattern and sphenoid deposition fraction of micro-particles were evaluated and compared for pre- and post-surgery cases. The presented results show that sphenoidotomy increased the airflow into the sphenoid sinus, which led to increased deposition of micro-particles in this region. Particles up to 25 μm were able to penetrate into the sphenoid in the post-operation case, and the highest deposition in the sphenoid for the resting breathing rate occurred for 10 μm particles at about 1.5%.

1. Introduction

Rhinosinusitis is one of the most common diseases that cause suffering for many patients. In order to treat those patients who do not respond to pharmaceutical medications, Endoscopic Sinus Surgery (ESS) is prescribed. Sphenoidotomy is used to relieve the infections, polyps, or tumors in the sphenoid sinus. The sphenoid sinus is one of the deepest and largest sinuses in the nasal passage. Sphenoidotomy is performed without resection of the turbinate and by creating an opening into the anterior wall of the sphenoid sinus or enlarging the natural ostium of the sphenoid sinus. If the surgeon approaches the sphenoid sinus through removal of ethmoid sinuses, then the procedure is called transethmoidal sphenoidotomy [1]. This procedure requires dissection of the uncinate process in order to visualize the natural ostium of the maxillary sinus. After identification of the anterior ethmoid area, its cells are dissected. Then posterior ethmoid sinuses are identified and dissected. Finally, the sphenoid is opened inferiorly and medially, and the ostium is enlarged laterally. Sphenoidotomy causes some alteration in the nasal airway structure. This leads to changes in airflow and deposition patterns of the inhaled particles in the nasal airway.

Before an actual surgery, a virtual surgery can be helpful for specialists and surgeons to assess the potential changes in both the nasal airflow and deposition of the aerosol particles. In addition, the virtual surgery would allow for testing various alternatives and for optimal surgical planning [2]. Recently, due to the rapid growth in computer technology, researchers have been able to prepare accurate 3-D computational models from CT scan images. Moreover, these nasal models can be virtually modified to reflect the predicted results of the proposed surgical techniques [3]. In contrast to experimental approaches, Computational Fluid Dynamics (CFD) techniques provide a powerful research tool to investigate the airflow in the human nasal airway [4–9], as well as transport and deposition of aerosol particles [10–15]. Even more complex transport processes such as elongated fiber deposition and stochastic effects of turbulence on particle motion can be studied numerically [16–19]. There have been several CFD studies of nasal airway models with surgical modifications. Lindemann et al. [20] simulated the airflow in the nasal cavity after a virtual radical sinus surgery during inhalation. They showed that aggressive turbinectomy leads to disturbed intranasal air conditioning caused by reduction of the surface area. Chen et al. [21] and Na et al. [22] investigated the effect of surgical turbinate resection on airflow characteristics. Surgical correction of septal deviation has

* Corresponding author. Tel.: +98 711 613 3034; fax: +98 711 647 3511.
E-mail address: abouali@shirazu.ac.ir (O. Abouali).

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been one of the common procedures in otolaryngology. Ozlugedik et al. [23] and Garcia et al. [24] carried out CFD studies on airflow in a nasal cavity model with septal deviation. Moghadas et al. investigated the impact of septal deviation on the deposition of nano/micro-particles in a human nasal passage using a computational modeling approach. Their results suggested that there would be marked changes in the deposition pattern of particles after septoplasty, surgery to straighten the nasal septum [25].

A number of numerical investigations of sinus-flow changes with surgical modifications have been reported in the literature [20,26,27]. Hood et al. studied the gas exchange in the maxillary sinus and scrutinized the effects of ostium size and the accessory ostium on the sinus ventilation rate [28]. Rennie et al. investigated sinus ventilation experimentally and numerically for single- and double-ostium sinuses [29]. Abouali et al. [2] constructed realistic 3-D computational models of the human nasal passage for pre- and post-virtual uncinectomy and Middle Meatal Antrostomy (MMA). They showed that after maxillary sinus endoscopic surgery, the maxillary sinus ventilation changes dramatically and the deposition of inhaled nano/micro-particles in the sinus increases.

In earlier studies of the human sinus-nasal flow, steady air and particle flow conditions have been assumed to simplify the computational modeling effort and cost. The significance of the transient nature of respiratory flows has already been pointed out by Shi et al. [12], Lee et al. [30], Zhu et al. [31,32] and Chung et al. [33], among others. The motion and deposition of inhaled particles during cyclic breathing, however, have been rarely studied. The exceptions are the studies of Zhang et al. [34] in a triple bifurcation lung airway model, the Takano et al. [35] analysis of the human larynx region, and the Inthavong et al. [36] simulations of micro-particle deposition in a tracheobronchial airway model. It is worth mentioning that only Häußermann et al. [37] experimentally investigated micro-particle deposition in the nasal airway using human breathing patterns. An unsteady model of nano-particle transport was also performed by Zhang and Kleinstreuer [38] and Shi et al. [12].

The presented literature survey shows that the numerical investigation of micro-particle transport and deposition in a nasal airway under unsteady condition (cyclic inhalation and exhalation) has not been reported in the literature. In addition, computational modeling of the ethmoidotomy and sphenoidotomy effects on the nasal airflow and deposition of inhaled pollutants and particles is missing. In the present study, a realistic human airway model was constructed, and a virtual sphenoidotomy operation was performed on the left nasal passage and sphenoid sinus. In order to capture the time-dependent characteristics of transport processes and the features of transient airflow structures, the full breathing cycles were simulated numerically under cyclic flow condition and the particle deposition pattern was investigated in the inhalation phase.

2. Computational model of the nasal airway

To create a three-dimensional model of the nasal cavity including paranasal sinuses for the pre- and post-operative cases, coronal cross sections for the left side of the nasal cavity and sinuses obtained by computed tomography (CT) scan images of a healthy adult male were used in this study. The scans consisted of coronal cross sections spaced 0.625 mm apart with a spatial resolution of 512×512 pixels from the tip of the nostrils to the beginning of the nasopharynx. The images were acquired as a part of the routine clinical procedure.

The boundary between the airway mucosa and air in the nasal cavity and paranasal sinuses was determined in each CT scan's slice under the supervision of a specialist. To reconstruct the 3-D model consisting of the nasal cavity and sinuses, the boundaries were connected to each other to create a smooth surface, and form the volume using commercial software. Finally, the model was exported as STL (Stereolithography) file format into ANSYS-ICEM software for meshing. Details of the modeling process of the human nose may also be found in the works of Zubair et al. [39,40]. Fig. 1 shows different views of the constructed model including the description of different parts. To produce the post-surgery model, the uncinectomy, ethmoidotomy and sphenoidotomy were performed virtually by the otolaryngologist through resecting the uncinate process and removing ethmoid cells and a part of the anterior wall of the sphenoid sinus on the coronal cross sections.

Fig. 2 shows the lateral view of the computational model with locations of several cross sections corresponding to an area that has undergone surgery. Comparison between cross sections pre- and post-operation is also shown.

Fig. 3 compares the variations of the cross-sectional areas of the nasal passage with the distance from the nostril for pre- and post-operation cases. It is seen that after surgery the nasal cross-section area has been enlarged compared with that before the surgery. The enlargement of the nasal passage was initiated from the uncinate process near the maxillary ostium at a distance of 52 mm from the nostril and continued to the sphenoid sinus region at a distance of 88 mm from the nostril. Fig. 4 shows the shape of the sphenoid for pre- and post-operative cases. It is seen that a portion of the anterior wall of the sphenoid around the sinus ostium has been removed.

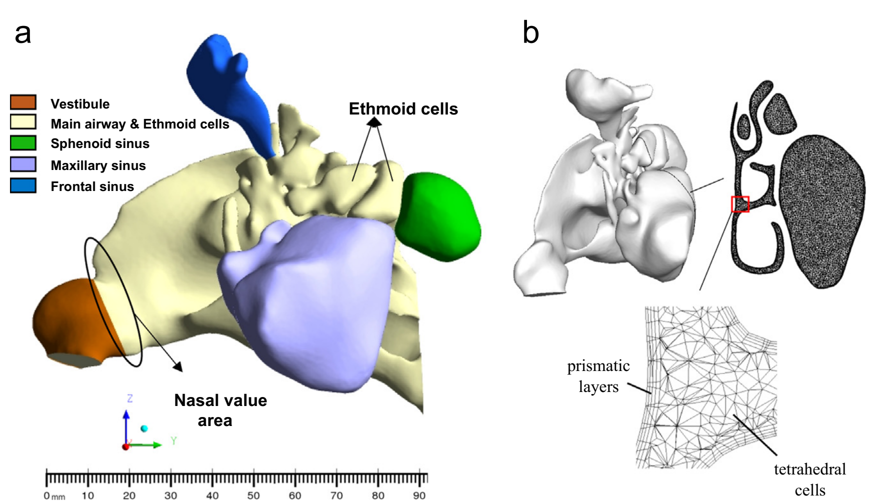

Fig. 1. (a) Schematic of the constructed nasal model and (b) one coronal cross section of generated hybrid mesh.