NUMERICAL SIMULATIONS OF UNSTEADY AERODYNAMIC FLOWS INSIDE A NASAL CAVITY WITH FUNCTIONAL ENDOSCOPIC SINUS SURGERY

Xiao Bing Chen1,*, Heow Pueh Lee1
1Department of Mechanical Engineering
National University of Singapore, Singapore
5 Lower Kent Ridge Road
Singapore 119260
*E-mail: mpecx@nus.edu.sg

Vincent Fook Hin Chong2, De Yun Wang3
2Department of Diagnostic Radiology, Yong Loo Lin School of Medicine
3Department of Otolaryngology, Yong Loo Lin School of Medicine
National University of Singapore, Singapore
5 Lower Kent Ridge Road
Singapore 119260

ABSTRACT
The aim was to evaluate the effects of Functional Endoscopic Sinus Surgery (FESS) on nasal aerodynamic flow patterns using Computational Fluid Dynamics (CFD) simulations. A 3-dimensional model of nasal cavity was first constructed from CT scans of a human subject with FESS interventions on left nasal cavity. Computational fluid dynamics (CFD) simulations were then carried out for unsteady airflow inside the nasal cavity as well as the sinuses. Comparisons of the local velocity magnitude and streamline distributions inside the left and right nasal cavity and maxillary sinus regions were presented. Existence and distributions of local circulations (vortexes) were found to be different at different phases, which showed the importance of local inertial effects especially in the sinus around FESS operated region. Possible outcomes on functional performances of the nose were also examined and discussed. Such physical assessments of nasal airflow based on a model from the patient's CT scans may help clinicians to determine the best treatment in advance.

KEY WORDS
Functional Endoscopic Sinus Surgery (FESS), nasal cavity, computational fluid dynamics (CFD), CT scan, nasal airflow.

1. Introduction
Functional Endoscopic Sinus Surgery (FESS) is commonly chosen for treatments of human nasal obstructions with refractory chronic rhinosinusitis. It can successfully and sustainably reduce the symptoms and severities of nasal obstructions [1, 2]. Evaluations of such a surgical procedure for subjective and objective improvements of nasal resistance, patency and normal functions have been carried out by using anterior active rhinomanometry [3], acoustic rhinometry [4] and nasal spirometry [2]. On the other hand, Computational Fluid Dynamics (CFD) study has recently become an emerging technology which provides an accurate and straightforward assessment of aerodynamics inside a healthy nasal cavity [5, 6, 7, 8, 9]. It offers a highly graphical model to better understand the nature of nasal airflow, which has not been previously possible with other techniques such as rhinomanometry or Mink box simulations.

Human respiration statuses are cyclic and periodic with maximum and minimum flow rates [10]. For the above mentioned numerical airflow simulations in the healthy nasal cavities, due to its relatively small Womersley number value [9], the airflows inside were usually assumed to be quasi-steady. However, for a nasal cavity with FESS, paranasal maxillary sinus regions are usually opened up and the main nasal cavity is enlarged. It will thus significantly increase local coronal cross sectional area and also Womersley number values. In this case, the airflow inside may not be appropriate to be simplified into a simple steady flow because local inertial effects on transient flow fields may become important.

Airflow was found to partially stream into the maxillary sinus regions, the upper ethmoid and sphenoid regions inside a nasal cavity with FESS interventions, as reported in a previous numerical study with a steady flow assumption [11]. On the contrary, the aim of this study was to evaluate the effects of FESS on unsteady nasal aerodynamic flow patterns using CFD tools. The nasal cavity model was constructed using CT scans from a patient with FESS interventions. Results were presented with local velocity magnitude and streamline distributions inside. Existence and distributions of local circulations (vortexes) were compared and their possible outcomes on functional performances were also discussed.

2. Materials and Methods
All personal identifiers of this patient have been removed before processing for the numerically experimental study. Institutional Review Board approval was obtained for this study. The individual patient (Chinese, adult male, 170 cm...
height and 66 kg mass) with conventional FESS procedure interventions on the left nasal cavity was considered here (CT scans presented in Figure 1). The left ostium into the left maxillary sinus was enlarged and the walls of ethmoid and sphenoid sinuses were partially removed. For the right cavity, there were fewer pathological abnormalities of interest and it could be regarded as a healthy side. Image acquisition, three-dimensional reconstruction, mesh grid formation and computational simulations followed the established techniques of our past reported studies [12, 13, 14]. The CT scans were taken at 1.5mm intervals and the structures of the internal nasal cavity were confirmed with endoscopy and acoustic rhinometry measurements in The National University Hospital, Singapore.

Three-dimensional (3D) nasal cavity model was reconstructed using several commercially available softwares such as MIMICS 13.0 (The Materilize Group, Leuven, Belgium), Hypermsh 10.0 (Altair Engineering, Bangalore, India), and TGrid 4.0 (ANSYS, Inc., Canonsburg, PA). CFD simulations were performed using Fluent 6.3 (ANSYS, Inc., Canonsburg, PA). A preliminary grid convergence survey was conducted for computing its sensitivity on local velocity and finally a typical nasal cavity model including paranasal maxillary, ethmoid and sphenoid sinuses comprising about 2.45 million tetrahedral cells was found to be adequate for ensuring insensitivity to mesh densities. The flow was assumed to be incompressible and un-steady. To account for the possible existences of turbulence, the Reynolds averaged Navier-Stokes equations were solved for the turbulence flow with $k-\omega$ model. An unsteady boundary velocity (airflow rate) at the nasopharynx area was applied [15].

$$U = U_{\text{max}} \left( 2 \sin^2 \left( \frac{\pi T}{\tau} \right) - 1 \right)$$  (1)

The above boundary velocity variations with time were shown in Figure 2, where peak boundary velocity $U_{\text{max}} = 2$ m/s (corresponding peak flow rate 20.4 L/min) and breathing period $\tau = 4$ s [15]. To compare the internal aerodynamic flow properties with the same flow rate but different phases, six time points ($T_1$ and $T_2$ for expiration status, $T_3$ and $T_4$ for inspiration status, $T_5$ and $T_6$ for quiet status) were chosen. At the external enclosure of the face, the pressure inlet boundary condition was applied with gauge pressure, equal to be atmospheric pressure.

(a) Typical coronal view  (b) Typical saggital view

Figure 1 Selected sections of the nasal cavity with FESS.

Figure 2 Time-dependent boundary condition at the nasopharynx.

3. Results and Discussion

Figure 3 shows the velocity magnitude contours of air-flows in a typical coronal cross section at selected times for expiration status.

(a) Acceleration phase ($T_1$)  (b) Deceleration phase ($T_2$)

Figure 3 Comparison of velocity magnitude of air-flows in a typical coronal cross section at selected times for expiration status.
cavity close to the FESS region, there are airflows entering the left maxillary sinus region. The overall flow features for acceleration (Figure 3a) and deceleration (Figure 3b) phases are similar. However, although the total airflow rates are the same for the two phases (about 14.4 L/min in Figure 2), relatively more air with relatively higher local velocity is found in the left maxillary sinus region at deceleration phase (time T2).

Figure 4 shows the velocity magnitude contours of air-flows in a typical coronal cross section at selected times for inspiration status. The airflow distributions are similar with those in Figure 3 and noticeable differences are also detected from the acceleration to the deceleration phases. However, relatively more air with relatively higher local velocity is found in the left maxillary sinus region at acceleration phase (time T3, note the scale differences from Figure 3). Further results show that the local velocities (pressure) around the enlarged ostium into the left sinus region are 1.52 m/s (-12.54 pascal) and 1.73 m/s (-13.69 pascal) for the acceleration and the deceleration phases, respectively. Total pressure loss from the nostril to the nasopharynx are 16.29 pascal and 15.61 pascal for times T3 and T4, respectively.

Figure 5 presents comparison of velocity streamlines of air-flows in another typical coronal cross section at selected time intervals for the inspirational status. Circulations are formed inside the left and right maxillary sinus regions, and there are greater changes of their location distributions inside the left one. This is because there is much smaller amount of airflow into the right maxillary sinus regions. The right ostium is not enlarged and the FESS intervention is only carried out on the left side. Such greater airflow pattern changes show that the inertial effects related to transient flow field cannot be neglected, especially around the FESS region, which may thus affect local mass and humidity transfer, and further local nasal normal patency.

Figure 6 shows the velocity magnitude contours with quiet statuses (T5 and T6 in Figure 2). It is seen that with the existences of inertial effects, even when the transient airflow rate is zero at the nasopharynx, there is still airflow with relatively higher velocity inside the left maxillary sinus region than the main nasal air passage around the turbinates. The largest local velocities inside the left sinus region are 0.14 m/s and 0.23 m/s at times T5 and T6, respectively. Distributions of different sizes and locations of circulations there are also found (not shown). Thus the inertia effects are more dominant in the maxillary sinus around the FESS region, and once local internal flow with circulations are formed there, their existences will be continuous through the whole respiration cycle.
4. Conclusion

The local velocity distributions were different around the FESS region inside a nasal cavity for the acceleration and deceleration phases, and also for different quiet phases especially inside the maxillary sinus around FESS region. The distributions of local circulations (vortices) inside were also different, which would affect nasal normal functions and other patencies. Thus the inertia effects are not negligible for CFD aerodynamic simulations inside a nasal cavity with FESS. Such physical assessments may benefit surgeons in planning and predicting aerodynamic effects for further treatments in advance.

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References


