Computational Otolaryngology – Modeling and Simulations of Nasal Airflows

***Heow Pueh Lee[1], Jianhua Zhu[1], Shu Jin Lee[2] and De YunWang[3]**

[1]Department of Mechanical Engineering, National University of Singapore, Singapore
[2] Division of Surgery, Yong Loo Lin School of Medicine, National University of Singapore, Singapore
[3] Department of Otolaryngology, National University of Singapore, Singapore

*Corresponding author: mpeleehp@NUS.EDU.SG

Abstract

There is a growing interest in the use of computational fluid dynamics (CFD) modeling and simulations with detailed nasal airway models constructed from CT or MRI images for surgical planning and assessment of outcome of nasal surgery. As compared to rhinomanometry and acoustic rhinometry, which provide quantitative information only of nasal airflow, resistance, and cross sectional areas, CFD enables additional informations of airflow passing through the nasal cavity that help visualize the physiologic impact of alterations in intranasal structures. Therefore, it becomes possible to quantitatively measure, and visually appreciate, the airflow pattern (laminar or turbulent), velocity, pressure, wall shear stress, particle deposition, and temperature changes at different flow rates, in different parts of the nasal cavity. The effects of both existing anatomical factors, as well as post-operative changes, can be assessed. With recent improvements in CFD technology and computing power, there is a promising future for CFD to become a useful tool in planning, predicting, and evaluating outcomes of nasal surgery. This presentation presents some of the recent studies performed in our research group related to clinical applications or assessment of nasal obstructions, Turbinectomy, Functional Endoscopic Sinus Surgery, Cleft palates and Rhinoplasty. I will also highlight our recent works in terms of modeling and simulations of nasal airflows due to the long duration wearing of N95 respirators.

Keywords: Computational Fluid Dynamics, Nasal Airways, Sinuses, Nasal Obstructions, Functional Endoscopic Sinus Surgery, Turbinectomy, N95 respirators

Introduction

The nose is the guardian angel of the respiratory tract. It has several important physiological functions which include air-conditioning, filtrating the inspired air, and smell. It also plays an important defence function, as the nose is the first place where foreign pathogens and allergens contact the host. To serve these important functions, a functional or patent nasal passage is essentially needed. A better understanding of how the nose functions is important and related to the treatment of respiratory related medical conditions such as snoring, Obstructive Sleep Apnea (OSA), and the contraction of diseases such as SARS and Bird Flu. Nasal obstruction is also a common complaint which is difficult to quantify clinically. The etiologic factors for nasal obstruction include anatomic variations of the nose and various local and systemic diseases. Hence, objective assessment of the nasal airway will aid diagnosis, treatment, research and medico-legal documentation.

During the last 10 to 20 years, attempts have been made to quantify nasal functionality or patency. This is an exciting time in the field of rhinology with regard to basic research and clinical practices. The technological advancements and greater insight into understanding of normal nasal functions and their relationship with other organs has spurred research in this field. Functional nasal airway measurement is important not only for research in nasal physiology, but is a useful and important diagnostic tool for patients with nasal or its related disorders. The sensation of nasal obstruction, nasal resistance and minimal cross sectional area are three distinct entities measuring nasal patency, which are closely related to each others. In a combination of these techniques, it represents the state of the art for a functional and quantitative study of the nasal airway. However, to date, it is still not possible to quantitatively measure the changes in nasal physiologic functions, which are caused by various type and degree of anatomical or pathophysiological changes of the nasal cavity and patency.

The relevance of objective assessment of nasal resistance and patency has been documented in many rhinological situations: (a) In routine rhinological practice, it is particularly useful in the differential diagnosis and management of common nasal diseases, e.g., allergic or non-allergic rhinitis and nasal septum deformity. Objective testing is useful in appropriate decision-making. Routine employment of objective quantitative assessment will result in improved diagnosis and the medical management. (b) Measurement of nasal airway patency is very much appreciated in rhinological research, since it provides a quantitative piece of information on the changes of nasal mucosal response to intranasal application with allergens and any kind of physical and chemical agents. (c) It provides objective data on the nature of nasal airway that can be used as the medicolegal documentation.

More recently, the advantages of computational fluid dynamics (CFD) enable researchers to obtain detailed flow patterns in the human upper airway by reconstructing models from computed tomography (CT) and Magnetic Resonance Imaging (MRI) images, which has become a new reliable trend of nasal airway exploration. However, there are very few reported comparisons of computational fluid mechanics simulation results with clinical measurements of airways conditions, let alone using the common techniques of rhinomanometry and acoustic rhinometry. It is generally agreeable that experimental investigations in nasal airway models give only limited compatibility with actual physiological conditions of the nose although the simplified experimental model allows for detailed examinations of various complicating effects. The lack of correlation studies between the engineering simulations and clinical practices, especially clinical examinations on actual nasal airway is a major reason as to why the engineering simulations have not found its way into the clinical examinations and also the lack of CFD related publications in clinical otolaryngology journals.

The present research currently being carried out in the Department of Mechanical Engineering, Department of Otolaryngology and Department of Surgery within the National University of Singapore is therefore an attempt to bridge this gap by correlating the engineering simulations to actual physiological functions of the nasal airways. The present study will also attempt to establish the relations between the engineering simulation results and the measurements from rhinomanometry and acoustic rhinometry. These two methods provide complementary and important objective information concerning the nasal airway

Rhinomanometry is well established as a useful clinical method for objective assessment of nasal patency. Nasal resistance to airflow is calculated from measurements of nasal airflow and transnasal pressure. Sstandardization of rhinomanometry was established in 1983 and accepted worldwide. The nasal resistance is calculated from the measurement of the nasal airflow at a fixed transnasal pressure point and is expressed in Pa/cm3/s. Three types of rhinomanometry can be used: active anterior rhinomanometry (AAR), active posterior rhinomanometry (APR), and passive anterior rhinomanometry (PAR). AAR uses a facemask, one nostril is sealed off with adhesive tape; a hard plastic tube passed through the tape measuring the nasopharyngeal pressure. It is a dynamic test that studies nasal ventilation; showing the nature of the air stream and a difference in the shape of the inspiratory and expiratory limbs at the individual nasal cavity. This method is well standardized and it is the most common and accurate method for clinical use. The major disadvantage of this method is that it cannot be performed in the presence of a septal perforation or a complete unilateral nasal blockage. For PAR, a fixed airflow of 250cm3/s is blown through a nozzle into one nostril. The pressure induced by the nasal resistance to this airflow at a given level of the nozzle is measured. This is an easy and fast procedure that can be used even in infants. Nasal patency measurement on one side is still possible when the other side is completely blocked. It has been proven to be a qualitative as well as a quantitative method for the objective evaluation of the degree of nasal obstruction in patients with allergic rhinitis following the nasal allergen challenge. However, the sensitivity and accuracy of this measurement is somewhat lesser than AAR.

In contrast, acoustic rhinometry does not measure airflow parameters but explores the geometry of the nasal cavity. The principle of acoustic rhinometry is that an audible sound (150-10,000 Hz), propagated in a tube, is reflected by local changes in acoustic impedance. This method provides estimates of cross-sectional endonasal areas and of the endonasal volume, and helps to define objectively the structural and mucosal components of the nasal passage. Since its introduction, there has been an explosion of research using this tool. Due to the rapid acquisition of data which can be completed in a minute, it has become a valuable clinical and research tool. Patient tolerance is excellent even in children.

The proposed research is multi-disciplinary and multi-physics in nature and will not be possible without close collaborative efforts among engineers, clinicians and biomedical researchers. By examining the engineering analysis results with the respective clinical observations and measurements performed using rhinomanometry and acoustic rhinometry for actual nasal models of various medical conditions, the engineering analysis can be developed into a virtual objective tool to be used in clinical otolaryngology and to help in a more accurate diagnosis and documentation of nasal conditions.

The main objective of this research is therefore to bridge the gap between the engineering analysis and simulations, and the clinical practices for assessing objectively the physiological conditions of nasal airways. The specific tasks are as follows:

- To establish computational models of human nose based on CT and MRI imaging for various nasal conditions.
- To investigate the relationship between the geometrical configuration of the nasal cavity and the simulated results for airflow and thermodynamic behaviour in healthy conditions and obstructive nasal diseases.
- To correlate the simulation results to the nasal conditions assessed by rhinomanometry, acoustic rhinometry and clinical examinations.
- To establish an in vitro nasal airway model with actual human nasal functional and physiological characteristics.
- To develop a virtual objective tool to be used in clinical otolaryngology and to help in a more accurate diagnosis and documentation of nasal conditions.

Methodology

The research performed involves both numerical and experimental studies. The main tasks for the numerical studies are modeling and simulations. Three dimensional surface models were first created by image segmentation of CT or MRI scans provided by the collaborators from clinicians. This was usually done using several commercially available softwares such as MIMICS 12.1 (The Materilize Group, Leuven, Belgium), Hypermesh 9.0 (Altair Engineering, Bangalore, India), and TGrid 4.0 (ANSYS, Inc., Canonsburg, PA, USA). Smoothing of the highly corrugated surfaces due to digitization was performed to facilitate computational meshing of the three-dimensional model. Smoothing of the boundary surface in such relatively larger 3-D nasal cavity will not affect the main flow pattern inside, but will help to decrease computational effort and increase computational efficiency. Computational fluid dynamics studies were carried out using Fluents for pure flow simulations or Adina for fluid structural interaction such as the interaction of soft plate and airflow for the analysis of obstructive sleep apnea. These tasks were performed at the Applied Mechanics Laboratory, National University of Singapore.

The human subject studies, conducted in two phases were conducted at the Investigator trial unit, National University Hospital. A total of 100 volunteers (47 for the first phase and 53 for the second phase) was recruited for this study. The first phase was conducted over a period of five days and the second phase was conducted for another three days. The typical tasks involved the completion of study questionnaires, the performance of acoustic rhinometry, rhinomanometry, mucociliary clearance evaluation using saccharin tests, and smell test using the University of Pennsylvania Smell Identification test kits,

Several nasal cavity models have been created based on CT or MRI of patients. The initial phase of the research focused on the analysis of nasal blockade or Inferior Turbinate Hypertrophy on the aerodynamic pattern and physiological functions of the turbulent airflow. Subsequent studies extended the flow simulations to particle deposition related to drug delivery as well as the thermal effect. The study was then extended to the other geometric effects such as septal deviation and septal perforation as well as the effect of various surgical procedures such as inferior turbinectomy and towards the later part of the research, on the effect of Functional Endoscopic Sinus Surgery (FESS) as well as nasal fractures. All the numerical simulations were examined and co-related to clinical observations and therefore most of the findings were in fact published in clinical journals related to otolaryngology such as the Laryngoscope, Rhinology, Journal of Aerosol Medicine and Pulmonary Drug Delivery, American Journal of Rhinology and Allergy, Respiratory Physiology and Neurobiology. As highlighted by one of the reviewers, there has been "a boom in the number of publications describing the flow patterns in the nasal cavity of various nasal pathologies, especially in clinical journals".

Results and Discussion

A major portion of the project is to examine the effect of various pathological conditions on the nasal functions. Two pathological conditions related to septal deviation and inferior turbinate hypertrophy are the main focus of the study.

In the nose model with septal deviation, major changes in the pattern of inspiratory airflow (e.g., flow partitioning and nasal resistance, velocity and pressure distributions, intensity and location of turbulence), wall shear stress and increasing of total negative pressure through the nasal cavity were demonstrated qualitatively and quantitatively. For the healthy nose, the main airflow occurs in the middle of the airway (between the inferior and middle turbinates around the septum), with the peak velocity in this area. On the contrary, in the model with a septal deviation, the main airflow is found passing through the floor (left side) and superior part (right side) of the nasal cavity. In the healthy nose, the area with the highest intensity of turbulent flow was found in the functional nasal valve region, but it became less apparent or even disappeared in the septal deviation one. For healthy case, the pressure decreases smoothly along the airway from nostril to the nasopharyngeal region. However, for deviated nose, greater pressure gradient or abrupt pressure jump is found posterior to the site of deviation (more in the right side than the left). For the deviated nose, the air flow mainly goes through the upper passageway in the cavity; two noticeable vortex areas are detected. Vortex areas mainly locate near the nasal valve region and dorsal regions near the superior cavity. With a large inspiratory flow rate of 34.8 L/min, maximum transient velocities of 5.69 m/s and 7.67 m/s are detected inside the healthy and septum deviation noses respectively. A higher shear stress distribution is found in the floor of the left nasal cavity than that in the right side. This CFD study provides detailed information of the aerodynamic effects of nasal septal deviation on nasal airflow patterns and their associated physiological functions.

In the healthy nose, the main respiratory air stream occurs mainly in the middle of the airway, accompanied by a diffused pattern of turbulent flow on the surface of the nasal mucosa. The peak value of turbulent flow is found in the functional nasal valve region. However, this aerodynamic flow pattern has partially or completely changed in the models with enlarged inferior turbinate. With an inhalation flow rate of 34.8 L/min, a maximum velocity of 5.69 m/s, 7.39 m/s and 11.01 m/s, are detected respectively in the healthy, moderately and severely obstructed noses. Both total negative pressure and maximum shear stress has increased by more than three and two times, respectively, in severely blocked noses compared to the healthy one. Data of this study provide quantitative and quantitative information of the impact of inferior turbinate hypertrophy on the aerodynamic pattern and physiological functions of nasal airflow. By including the model of turbulent airflow, the results of this experimental study will be more meaningful and useful in predicting the aerodynamic effects of surgical correction of the inferior turbinate hypertrophy.

Nasal patency is an essential condition that has a major impact on particle deposition. For the healthy one, due to its complete existence of the MCA, the particle number escaping the cavity is the largest one; for moderately blocked nose, due to its relatively larger penetration via MCA (two thirds left) than the severely blocked one (one third left), the particle number escaping the cavity is larger than the severely blocked one. The particle percentage escaping the nasal cavity decreased to less than a half and one tenth for the moderately and severely blocked noses. Decreasing of flow rate and particle diameter increased the escaping ratio; however, zero escaping percentage was detected with the absence of airflow and the effect was less noticeable when the particle diameter was too small. The existence of inspiratory flow and head tilt angle helped to change the particle escaping ratio for the healthy nose; however, such changes were not significant for the moderately and severely blocked noses. Thus it is noted that the patients with nasal obstruction need to ensure the presence of a middle inspiratory flow rate, when using the nasal spray device for higher escaping ratio. To insert the spray deeper with particles beyond the MCA region or a decongestive treatment to increase the MCA may be necessary in patients with moderately or severely blocked noses as the effects of the changes of nose flow rate, initial particle velocity, particle diameter and head tilt angles for drug delivery are limited or even negligible.

Another major portion of the research is the evaluation of surgical procedure on nasal airflow and particle deposition. The aim for one of these studies was to evaluate the effects of inferior turbinate surgery on nasal airway heating capacity using computational fluid dynamics (CFD) simulations. Heat transfer simulations were performed for a normal nasal cavity and others with severely enlarged inferior turbinates, before and following three simulated surgical procedures: (1) resection of the lower third free edge of the inferior turbinate, (2) excision of the head of the inferior turbinate and (3) radical inferior turbinate resection. The models were run with three different environmental temperatures. The changes of airflow pattern with the reduction of inferior turbinate were found to affect heat transfer greatly. However, the distribution of wall heat flux showed that the main location for heat exchange was still the anterior region. Under the cold environment, the nasal cavities with the head of inferior turbinate reduction were capable of heating the inspired air to 98.40% of that of the healthy one; however, for the case with lower third of inferior turbinate excised, the temperature was 11.65% lower and for the case with radical inferior turbinate resection, 18.27% lower temperature compared to the healthy nasal cavity. The healthy nasal cavity is therefore deemed to be able to warm up or cool down the inspiratory airflow under different environmental temperature conditions; for the nasal cavities with turbinate surgeries, partial inferior turbinate reduction can still sustain such heating capacity. However, too much or total turbinate resection may impair the normal function of temperature adjustment by nasal mucosa.

In another piece of work, we examined the effect of nasal surgery on particle deposition and drug delivery. Intranasal medications are commonly used in treating nasal diseases. However, technical details of the correct usage of these medications for nasal cavity with obstruction are unclear. A 3-dimensional model of nasal cavity was constructed from MRI scans of a healthy human subject. Nasal cavities corresponding to healthy, moderate and severe nasal obstruction were simulated by enlarging the inferior turbinate geometrically, which was documented by approximately one third reduction of the minimum cross sectional area for the moderate and two thirds for the severe obstruction. The discrete phase model based on steady state computational fluid dynamics was used to study the gas-particle flow. The results were presented with drug particle (from 7x10-5 to 10-7 m) deposition distribution along the lateral walls inside these three nasal cavities and comparisons of the particle ratio escaping from the cavity were also presented and discussed. Nasal patency is an essential condition that had the most impact on particle deposition of the factors studied; the particle percentage escaping the nasal cavity decreased to less than a half and one tenth for the moderately and severely blocked noses. Decreasing of flow rate and particle diameter increased the escaping ratio; however, zero escaping percentage was detected with the absence of airflow and the effect was less noticeable when the particle diameter was very small. The existence of inspiratory flow and head tilt angle helped to improve the particle escaping ratio for the healthy nose; however, such changes were not significant for the moderately and severely blocked noses. Therefore, when using an intranasal medication, it is advisable to have a moderate inspiratory airflow rate and small size particles in order to improve particle escaping ratio. Various head positions suggested by clinicians do not seem to improve drug escaping ratio significantly for the nasal cavities with inferior turbinate hypertrophy.

Another surgical procedure that has been examined is Functional Endoscopic Sinus Surgery (FESS). For the nasal cavities with FESS, the ostia may be enlarged and some ethmoid cells may also be removed. Therefore more airflow may be directed into the paranasal sinus regions, upper ethmoid and sphenoid sinus regions and thus affects their physiological functions. Moreover, the airflow inside was inappropriate to be assumed quasi-steady due to increased local Womersley and Strouhal numbers and increased local inertial effects.

Thus the study focused on the evaluation of the effects of a particular FESS case on unsteady nasal aerodynamic flow patterns and to attempt to answer whether there were existences of circulations inside the sinus regions. Different from previous steady state flow modeling, the study focused on unsteady airflow characteristics to investigate inertia effects. A 3-dimensional model of nasal cavity was constructed from CT scans of a patient with FESS interventions on right side nasal cavity. CFD simulations were then carried out for unsteady aerodynamic flow modeling 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 carried out. Due to the FESS procedures in the right nasal cavity, existences and distributions of local circulations (vortexes) were found to be significantly different for a same nasal airflow rate but at different acceleration, deceleration or quiet phases in the maxillary sinus region on the FESS side. Due to inertia effects, local internal airflow with circulation existences was continuous throughout the whole respiration cycle. With a larger peak inspiration flow rate, the airflow intensity inside the enlarged maxillary sinus increased significantly.

The current model was the first attempt to investigate such abnormal aerodynamic behavior around the FESS and sinus regions with transient airflow conditions. Although the current model is based on one particular individual and may not be representative for FESS procedures, it still provides qualitative and quantitative information for better knowledge of the internal geometrical changes with surgical effects on aerodynamic differences. Existences of airflow circulations or re-circulations inside the main nasal cavity volume were found for healthy nasal models. It was usually believed that the airflow going into the sinus region was negligible for a healthy nose, and possibly a small amount of airflow into the sinuses through ostia helped to maintain stable mass (nitric oxide) and humidity exchanges for the nasal cavity after the current manner of FESS, relatively larger amount of airflow were circulated into these regions and affected the local aerodynamic flow patterns. From engineering perspective, the open airway passage from the paranasal sinus regions to the nasal cavity behaves as a hollow cavity, which results in relatively smaller local pressure distribution with flow instability. Moreover, it was usually believed that the sinus regions were parts of the possible locations for productions of nitric oxide (NO). A relatively stable concentration of NO is needed to maintain a sterile local environment for a nasal breathing and respiratory systems to ensure normal functions related to human being host defense and local immunologic reactions. An uncinate process probably has a protective role in preventing deposition of bacteria and allergens in the sinuses during the inspirational phase. Thus for the current FESS case with the removal of uncinate process, the existences of continuous airflow and circulations inside the sinus regions may affect local nitric oxide re-distributions and its stability. Moreover with such circulations, bacterial infection rates may increase with possible depositions of bacteria and allergens in the sinus after FESS.

The first phase of the human subject study demonstrated the concordance of all the various clinical tests used in the assessment of nasal physiology in allergic and healthy volunteers. Impaired nasal function due to temperature change was found to be more exaggerated in allergic rhinitis. Dynamic interval functional assessment at (e.g. rhinomanometry, nasal spirometry) can better accentuate and demonstrate nasal hypersensitivity as compared to traditional single-point static testing. The preliminary findings of the second phase of human subject study showed that the airway is likely to be blocked more with smaller nasal valve minimal cross sectional area why lying down compared to body upright position. This will cause a shift of the frequency spectrum of the breathing sound. Detailed analysis is being carried out.

The team is currently embarking on the experimental study of “Objective Assessment of the Effects of long-duration wearing of N95 and surgical facemasks on upper airway functions” funded by the Ministry of Health involving 100 healthcare workers from the local hospitals and clinics.

A list of the publications arising from the research is appended in the list of references.

Conclusion

The existing CFD technology enables detailed study and objective measurements of the physical characteristics of the airflow within the anatomically exact numerical human nose models, which are constructed based on CT scan or MRI images. Although the predicted results from CFD study are derived from complex calculations which may not represent real life conditions, it does provide clinically useful and additional information in additional to typical clinical assessment such as rhinomanometry and acoustic rhinometry of the breathing airflow. Information that could be obtained from modeling and simulations include airflow pattern (laminar or turbulent), velocity, pressure, wall shears stress, and temperature changes under different flow rates in different part of nasal cavity, as well as the effect of various anatomical factors (e.g., septal deviation or perforation, inferior turbinate hypertrophy and turbinectomy, nasal and maxillary bone fracture, opening of rhinosinuses after surgery, and etc.). With the improvement in CFD technology and research, there is a promising future of this technique to become a useful tool in predicting outcomes and planning of nasal surgery.

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