CFD ANALYSIS OF VIRTUAL SURGERY FOR PATIENT WITH CHRONIC SINUSITIS

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Abstract— This paper focuses on performing virtual surgery on pre-operation nasal cavity model of patient with chronic sinusitis and evaluate the effects of virtual surgery on the patient's nasal airflow. Advancement in Computational Fluid Dynamics (CFD) allows better observation of human nasal airflow and opens up various opportunities for treatment planning. The application of CFD was used to construct numerical simulations of nasal airflows for the pre and post virtual surgical models. Patient with chronic sinusitis was selected and three-dimensional nasal model was constructed based on CT scans. A virtual surgery was performed via manual modifications on the disease nasal model using CATIA V5 software. The results and effects of the virtual surgery on the nasal airflow were analyzed and compared with standardized nasal model. Pre and post virtual surgery conditions of the patient can be studied through various data collections such as cross sectional areas, average velocity magnitudes, velocity contours and streamlines. The analysis of the virtual surgery model shows satisfying results as the average velocity magnitudes match closely with standardized model with the differences of less than 30% at middle region. The findings highlight the potential usefulness of CFD-generated numerical simulation as a pre-operative assisting tool in surgical treatment planning for chronic diseases.

Keywords— CFD, Computational Analysis, Chronic Sinusitis, Nasal Airflow & Virtual Surgery.

I. INTRODUCTION

The main requirement for a healthy nasal cavity is to perform respiration with undisturbed passage through the nasal airways. Two nasal cavities are separated by a nasal septum symmetrically. A nasal airway is mainly composed of three passages, which are inferior, middle and superior airway enclosed by the nasal septum. The nasal cavity is a hollow space within the nose and skull with full of hair and mucus membrane. The inhaled air will be filtered, warmed, and humidified before reaching the lung and providing oxygen. Nasal cavity protects the lung from the bad effects of inspired particles and environmental air pollutant particles, which is harmful to the lung.

Most infections occur in sinuses that open into the middle meatus; the area between the lower and the middle turbinate, namely the maxillary, the anterior ethmoid and the frontal sinuses [1]. Sinusitis can be considered as one of the complications of allergic rhinitis which will result in nasal mucosal oedema that may obstruct the sinus ostium and an increase in the production of mucous in the sinus caused by the allergic inflammation that occurs in the sinus mucosa and thus, causing the mucociliary apparatus to be impaired[2]. Sinusitis was chosen to be studied in this paper as it is a very common chronic illness with a substantial health care impact and as claimed by Hamilos, sinusitis is one of the most important diseases treated by allergy and immunology sub-specialists[3]. In 1996, sinusitis affects an estimated of 14% of the adult population in the United States with health care cost estimated to be more than 5.8 billion dollars[4, 5]. Based on the research from the Centers for Disease Control and Prevention (CDC), the number of adults with diagnosed sinusitis was estimated to be 28.5 million up to the year 2012. However, the condition was considered to be under-diagnosed as many patients believed that their symptoms were not sinus related but mainly due to persistent colds. In addition of this condition, the estimation can reach up to 30 million patients[6]. Sinusitis is often very frustrating and difficult to treat and thus, requires surgical treatment and sometimes will lead to repetitive surgery treatment which will bring pain to the patients and also costly[3].

The complex structure of human nasal cavity causes difficulties for direct measurement methods to obtain certain information related to nasal airflow. The most common objective measurement techniques for nasal function, which are acoustic rhinometry and rhinomanometry, still render ambiguities and inconsistencies in the results obtained[7]. An alternative method to construct a physical experiment is to perform CFD analysis. This technique consists of simulating the motion of fluid in certain environment. Human nasal model was built based on CT scans or MRI images, and the fluid was allowed to pass through the model to simulate normal breathing cycle. Analysis results were obtained in term of velocities in different sections along the nasal cavity. The advantages of CFD analysis compare to physical experiment is the solution provides complete and detailed analysis result of the velocity, pressure and temperature. CFD allows nasal cavities to be depicted exactly from the human nasal model and able to display the airflow pattern along the nasal cavity[8, 9]. A better understanding of the nose physiology, patho-physiology of normal breathing and the post-processing techniques of the flow patterns in nasal cavities can be achieved using

CFD[10-12]. In order to obtain vital information for any treatment, healthy and standard models are required for comparison purposes [8, 13, 14].

The most significant advantages of the usage of CFD analysis in evaluation of nasal pathologies are the ability of assessing local aerodynamics at any point inside the nasal cavity and the chance of investigating the aerodynamic effects of planned surgical interventions via performing virtual operations on models[15]. Such studies may not only help foresee the aerodynamic effects of operations, but also increase the success rate of surgical treatments. Therefore, this paper discusses the effects of virtual surgery on patient with chronic sinusitis. In near future, it may be feasible to simulate the nasal disorder before performing a surgical procedure on every patient. Thus, increasing the effectiveness of surgical planning and ultimately the outcome of the patients[16-21].

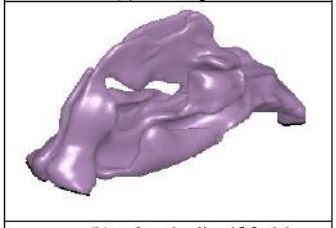
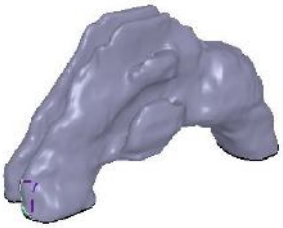
II. MATERIALS AND METHODS

CFD is a well-established method to make accurate prediction about fluid behaviors. With the help of CFD, rhinologist will be able to visualize nasal airflow characteristics in three dimensional views, study the relationship between cross-sectional area, pressure and velocity with various mass flow rates [22, 23]. The methodology implemented for this research involved the creation of 3D models from CT scans of an adult female patient. The 3D model was imported in ANSYS 16.0 for meshing and running the numerical simulation. Computational analysis was carried out to analyze the effects of virtual surgery on the patient.

2.1. Construction of 3D Nasal Model and Virtual Surgery Methods

The 3D model of nasal cavity was created using the segmentation with an appropriate threshold values in MIMICS. Several steps were involved in creating the model such as thresholding, editing the images and also creating the masks for the model. These functions were used to eliminate unwanted areas and to distinguish soft tissues, bone structures as well as empty spaces. The high resolution of the CT scans obtained ensures the accuracy of the geometry developed by the software. All the contours and complicated structures were maintained as much as possible to ensure that the model produced is similar to the real nasal cavity. The polylines model created from MIMICS was then imported to CATIA V5 to carry out the virtual surgery. Virtual surgery was performed via modification of the nasal model to produce nasal model with clear and unblock nasal airway. Table 1(a) shows the pre-operation nasal model with hollow area in the middle of the nasal cavity. This shows that there is no airflow passing through and virtual surgery was carried out to remove the blockage. Unwanted elements were removed from the surfaces and new surfaces were reconstructed again to fill up the middle hollow region by using suitable mean surface deviation and details parameters. Comparisons were carried out between the patient's nasal model (pre and virtual) with the healthy standardized model obtained from Lee et al. as shown in Table 1(b) to analyze the effects of virtual surgery in restoring the blocked nasal passageway [13]. Finally, the virtual operation model was converted to solid 3D model as shown in Table 1(c) and then, exported to ANSYS 14.0 for meshing and running analysis.

Table 1: Nasal Models Comparisons

(a) Pre-operation

(b) Standardized Model

(c) Virtual operation


2.2. Meshing of Geometry

Meshing is a process of dividing the entire domain into small, non-overlapping sub-domains. In this study, unstructured mesh was used for analysis due to the complex geometry of the nasal models. It is important to obtain a mesh configuration that gives high quality and sufficient number of meshing elements [24]. The grid independence study was performed to determine the best mesh from compromising between accuracy of the results obtained and computational time using unstructured tetrahedral meshing ranging from approximately 700,000 to 2,000,000 elements as controlled by the interval size settings. Previous researches used meshing elements of approximately 400,000 to 1,500,000 elements[9, 10, 13]. The mesh with 1,194,438 elements was chosen for further analysis. It was found that about 1,000,000 elements per one cavity gave good compromise between the accuracy

and the computational cost [25]. The similar mesh settings were maintained for virtual surgical model as well.

2.3. Running Analysis

Complete description of the fluid field can be captured at every part of the model via CFD [23]. All numerical simulations for this research were performed on the meshed geometries using ANSYS 14.0 (FLUENT). It is necessary to define boundary condition as a basis for the computational simulation. The boundary conditions that were defined included the wall of the model (to define the boundary between inner and outer nasal cavity), the mass flow inlet (to define an inlet based on mass flow rate as its parameter which is located at the nasal vestibules) and outflow (to define an outlet as located at the end of nasopharynx) [26]. Nasal hair was not considered as it is proven that it has no significant effect on the flow within the nasal cavity and the main interest in the studies is the major flow phenomena [27, 28]. The nasal wall was assumed to be rigid, with no slip boundary condition and effects of mucous was not considered due to its minimal thickness and low velocity [9, 29-32]

Several assumptions were applied to match the normal human breathing environment. The flow was assumed to be incompressible because the typical velocity of the nasal airflow is much smaller than the sonic velocity ($M < 0.3$) and thus, constant fluid properties were used [14, 16, 23, 25]. A pressure-based solver with second order upwind scheme approach was implemented in order to obtain sufficiently accurate solutions [12, 30]. In this study, the mass flow rate used for laminar airflow simulation are 125 ml/s and 200 ml/s. The inspiratory flow rate for healthy adults is range between 80 - 200 ml/s for light breathing and 200 - 660 ml/s for non-normal conditions such as during exercises [10, 33].

III. RESULTS AND DISCUSSION

Results obtained from this research are presented and discussed in three parts. The first part is the geometrical comparisons of chronic sinusitis nasal cavities, while second part is focused on the cross-sectional areas along the nasal cavities. Finally, the last part is focused on the numerical simulation results such as velocity magnitudes, contours and streamlines that were obtained from ANSYS (FLUENT).

3.1. Geometrical Comparisons

Geometric configuration plays a significant role in the flow distribution inside the nasal cavity [12]. Table 1 shows comparisons of 3D nasal models for pre and virtual operation with standardized model. Pre-operation nasal model refers to the chronic sinusitis nasal cavity. The hollow area in the middle region of the model as observed in Table 1(a) shows that there is blockage in that area and causing airflow to be blocked and disturbed. The blockage can be due to the inflammation and swollen of the sinuses and can caused the patient to face difficulties in breathing. The patient will suffer stuffy nose, reduction in sense of smell and facial pain. Other symptoms may include fever, headaches, cough, tiredness and many more [34]. Meanwhile, Table 1(b) shows healthy standardized model obtained from Lee et al. with clear passageway and no blockage observed along the nasal airway [14]. For virtual operation model as shown in Table 1(c), the blockage was cleared via editing the geometry in CATIA V5, therefore, no hollow region (no sign of airway blockage) and this model shows similarities with the standardized model in Table 1(b). For virtual operation model, only middle part of the nasal cavity was modified. The regions around the vestibules, nasal valves and nasopharynx remain unchanged. The virtual operation does not rebuild the middle meatuses and superior meatuses as it is not practical and cannot be achieved in actual surgical operation.

3.2. Cross Sectional Areas

The differences and comparisons in the 3D geometrical models as shown in Table 1 can be observed clearly based on the graphs of cross sectional areas as given in Fig. 1. Standardized model was utilized as a guideline for comparisons in order to restore the nasal airway back to normal. The cross sectional areas of the nasal cavities were obtained by creating planes from inlet to outlet at a distance 0.5 cm from each other, perpendicular to y-axis and parallel to z-axis. At the distance of 2 to 7.5 cm from the inlet, the cross sectional areas of the virtual operation are obviously larger than pre-operation. This region was the main concern in virtual surgery as clearing the blockage was carried out by enlargement and widening of this region.

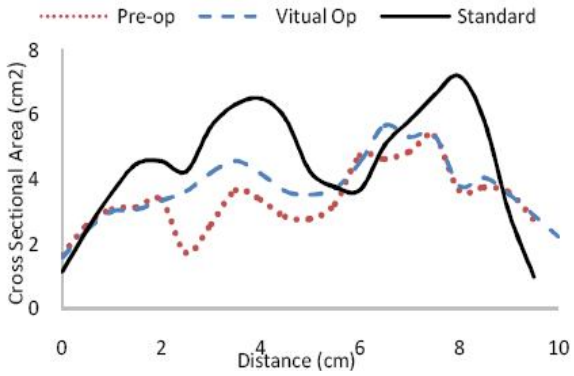


Figure 1: Cross sectional areas comparisons

3.3. Numerical Simulation Results

The effects of the virtual surgery can be observed and compared in terms of average velocity magnitudes, velocity contours and streamlines obtained from numerical analysis which was carried out for inhalation at mass flow rate of 125ml/s.

a) Average Velocity Magnitude

Average velocity magnitudes along the nasal cavities for pre-operation, virtual operation and standardized model can be observed from Fig. 2. The average velocity magnitude of pre-operation model is the highest among all the models due to narrow and congested nasal airway. Inhalation with very high average velocity magnitude causes the patient to feel breathing difficulties and in severe cases, leads to empty nose syndrome. The main purpose of the surgery is to restore undisturbed airflow passageway inside the nasal cavity. The virtual operation was performed to clear the blockage in the middle region by referring to standard model as guideline. This causes the increase in cross sectional areas and manages to lower down the average velocity magnitude by 34%. This shows that the airflow of virtual surgery model is closer to achieve the airflow of standard model. The differences between virtual and standard model are due to inter-individual differences as the models used were obtained from different subjects.

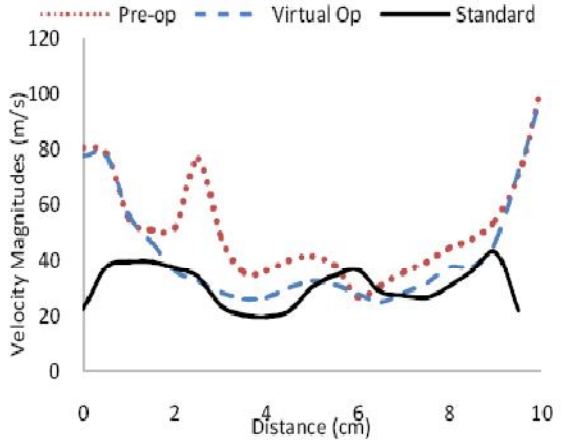


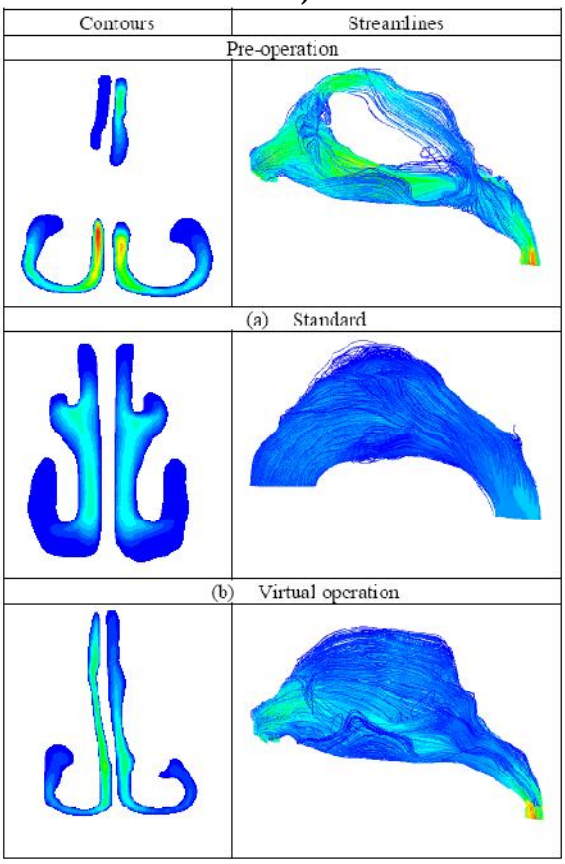
Figure 2: Graph of average velocity magnitudes along the nasal cavity (125 ml/s)

b) Velocity Contours and Streamlines

Nasal airflow behavior can be observed and analyzed better via velocity contours and streamlines of pre-operation, virtual operation and standard models as shown in Table 2. By observing the velocity contours and streamlines of the pre-operation model in Table 2(a), the highest velocity is observed in the center region and lowest velocity at the end of inferior meatuses and olfactory regions. After nasal valve, the streamlines consist of multiple flow circulations before moving into the turbinate region. Large circulations can be observed at the nasopharynx as the airflow changes from horizontal to downward direction. Plus, the airflow at the middle region is totally blocked and most of the airflow focuses on the lower region with low velocity airflow flowing through the upper region. These low velocity and lack of streamlines in the nasal cavity is one of the reasons for the patient to be uncomfortable and feel lack of oxygen during respiration.

The virtual operation as shown in Table 2(c) recovers the airflow in the middle region for both left and right cavities. However, the operation only modified the center region and does not recover the middle meatuses. This was carried out with consideration that majority of the airflow focuses along the nasal septum and recovering middle meatuses are not practical in actual surgical treatment. The close similarities between the virtual operation and standard model can be observed by comparisons of Table 2(b) and Table 2(c). This can be supported with the graph of average velocity magnitudes in Fig. 2 which proves that the virtual surgery manages to recover the airflow velocity magnitudes close to healthy standard condition. The operation allows more airflow to pass through the left and right nasal cavities as the distribution of airflow can be observed along the nasal cavity. Implementation of virtual surgery allows detailed observation of the impact from surgical treatment. Using this information, rhinologist will be able to analyze the best treatment planning for patients with chronic sinusitis.

Table 2: Velocity contours and streamlines (125 ml/s)



CONCLUSION

CFD simulations improve the understanding of the complex nasal anatomy and the implications of disease and surgery. It offers the potential for planning surgery and is possible to simulate surgery

by correcting the perceived anatomical abnormalities on the model called 'virtual surgery' and then, compare the flow predictions in order to help surgeon or rhinologist to decide whether a minor or major corrective surgery are required [22]. Effects of virtual surgery was analyzed by comparisons with pre-operation and standardized model. The virtual surgery simulates the model by correcting the perceived anatomical abnormalities on the model. By implementing virtual surgical analysis, detailed observations on the impact of the surgical treatment such as cross-sectional areas, velocity magnitudes, contours and streamlines can be observed in details and thus, allowing chances for improvement and corrections if there is any inadequacies or insufficiencies. This information will be very beneficial for rhinologist as a pre-operative tool to assist in clinical decision making.

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REFERENCES

[1] M. Wagenmann and R. M. Naclerio, "Anatomic and physiologic considerations in sinusitis," Journal of Allergy and Clinical Immunology, vol. 90, pp. 419-423, 1992.

[2] R. G. Slavin, "Sinusitis," Journal of Allergy and Clinical Immunology, vol. 73, pp. 712-716, 1984.

[3] D. L. Hamilos, "Chronic sinusitis," Journal of Allergy and Clinical Immunology, vol. 106, pp. 213-227, 2000.

[4] R. S. Leung and R. Katial, "The Diagnosis and Management of Acute and Chronic Sinusitis," Primary Care: Clinics in Office Practice, vol. 35, pp. 11-24, 2008.

[5] N. F. Ray, J. N. Baraniuk, M. Thamer, C. S. Rinehart, P. J. Gergen, M. Kaliner, S. Josephs, and Y.-H. Pung, "Healthcare expenditures for sinusitis in 1996: Contributions of asthma, rhinitis, and other airway disorders," Journal of Allergy and Clinical Immunology, vol. 103, pp. 408-414, 1999.

[6] A. Kaplan, G. J. Crosby, and N. Bhattacharyya, "Airway Protection and the Laryngeal Mask Airway in Sinus and Nasal Surgery," The Laryngoscope, vol. 114, pp. 652-655, 2004.

[7] M. Wolf, S. Naftali, R. C. Schroter, and D. Elad, "Air conditioning characteristics of human nose," The Journal of Laryngology & Otology, vol. 118, pp. 87-92, 2004.

[8] I. Weinhold and G. Mlynski, "Numerical simulation of airflow in the human nose," European Archives of Oto-Rhino-Laryngology, vol. 261, pp. 452-455, 2003.

[9] C. F. Lee, K. A. Ahmad, R. Ismail, and S. A. Hamid, "Numerical Study of Mucous Layer Effects on Nasal Airflow," Biomedical Engineering: Applications, Basis and Communications (BME) vol. 24, pp. 327-332, 2012.

[10] J. Wen, K. Inthavong, J. Tu, and S. Wang, "Numerical simulations for detailed airflow dynamics in a human nasal cavity," Respiratory Physiology & Neurobiology, vol. 161, pp. 125-135, 2008.

[11] S. Zachow, A. Steinmann, T. Hildebrandt, and W. Heppt, "Understanding nasal airflow via CFD simulation and visualization," Proc. Computer Aided Surgery around the Head, pp. 173-176, 2007.

[12] J. Wen, K. Inthavong, Z. F. Tian, J. Y. Tu, C. L. Xue, and C. G. Li, "Airflow Patterns in Both Sides of a Realistic Human Nasal Cavity for Laminar and Turbulent Conditions," presented at the 16th Australian Fluid Mechanics Conference, Crown Plaza, Gold Coast, Australia, 2007.

[13] C. F. Lee, M. Z. Abdullah, K. A. Ahmad, and I. L. Shuaib, "Standardization of Malaysian Adult Female Nasal Cavity," Computational and Mathematical Methods in Medicine, vol. 2013, pp. 1-11, 2013.

[14] C. F. Lee, M. Z. Abdullah, K. A. Ahmad, and I. L. Shuaib, "Analytical Comparisons of Standardized Nasal Cavity," Journal of Medical Imaging and Health Informatics, vol. 4, pp. 14-20, 2014.

[15] S. Ozlugedik, G. Nakiboglu, C. Sert, A. Elhan, E. Tonuk, S. Akyar, and I. Tekdemir, "Numerical Study of the Aerodynamic Effects of Septoplasty and Partial Lateral Turbinectomy," The Laryngoscope, vol. 118, pp. 330-334, 2008.

[16] S. C. Leong, X. B. Chen, H. P. Lee, and D. Y. Wang, "A review of the implications of computational fluid dynamic studies on nasal airflow and physiology," Rhinology, pp. 139-145, 2010.

[17] U. Bockholt, G. Mlynski, W. Muller, and G. Voss, "Rhinosurgical therapy planning via endonasal airflow simulation," Comput Aided Surg, vol. 5, pp. 175-9, 2000.

[18] A. Steinmann and S. Zachow, "Ansys CFX simulation of nasal airflow - Flow investigation and evaluation of nasal anatomy to support treatment planning for functional rhinosurgery," presented at the 24 CADFEM Users' Meeting 2006, International Congress on FEM Technology with 2006 German ANSYS Conference, Schwabenlandhalle Stuttgart/Fellbach, Germany, 2006.

[19] J. Pennecot, M. Ruetten, R. Kessler, and C. Wagner, "CFD mesh of the human nose and flow simulation," presented at the 8th.World Congress on Computational Mechanics (WCCM8), 5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008), Venice, Italy, 2008.

[20] S. Zachow, A. Steinmann, T. Hildebrandt, R. Weber, and W. Heppt, "CFD Simulation of Nasal Airflow: Towards Treatment Planning for Functional Rhinosurgery," International Journal of Computer Assisted Radiology and Surgery, pp. 165-167, 2006.

[21] C. Croce, R. Fodil, M. Durand, G. Sbirlea-Apiou, G. Caillibotte, J.-F. Papon, J.-R. Blondeau, A. Coste, D. Isabey, and B. Louis, "In Vitro Experiments and Numerical Simulations of Airflow in Realistic Nasal Airway Geometry," Annals of Biomedical Engineering, vol. 34, pp. 997-1007, 2006.

[22] N. Bailie, B. Hanna, J. Watterson, and G. Gallagher, "An overview of numerical modelling of nasal airflow," Rhinology, vol. 44, pp. 53-57, 2006.

[23] P. C. Ruiz, F. C. Ruiz, A. C. López, and C. C. Español, "Computational fluid dynamics simulations of the airflow in the human nasal cavity," Acta Otorrinolaringol Esp, vol. 56, pp. 403-410, 2005.

[24] M. Kleven, M. Melaaen, M. Reimers, J. Rotnes, L. Aurdal, and P. Djupesland, "Using Computational Fluid Dynamics (CFD) to Improve the Bi-Directional Nasal Drug Delivery Concept," Food and Bioproducts Processing, vol. 83, pp. 107-117, 2005.

[25] S. K. Kim, J. H. Park, Y. Na, and S. K. Chung, "Experimental and Numerical Study on the Airflows in Four Asymmetric Nasal Cavities Due to Deviated Nasal Septum," presented at the 6th World Congress of Biomechanics (WCB 2010), Singapore, 2010.

[26] K. Smith, "CFD Analysis of Pressure and Flow Characteristics of the Human Nose," Degree of Bachelor of Science Bachelor Degree, Faculty of the Worcester Polytechnic Institute, Worcester Polytechnic Institute, Worcester, Massachusetts, United States, 2008.

[27] I. Hörschler, M. Meinke, and W. Schröder, "Numerical simulation of the flow field in a model of the nasal cavity," Computers and Fluids, vol. 32, pp. 39-45, 2003.

[28] I. Hahn, P. W. Scherer, and M. M. Mozell, "Velocity profiles measured for airflow through a large-scale model of the human nasal cavity," Journal of Applied Physiology, vol. 75, pp. 2273-2287, 1993.
[29] C. F. Lee, K. A. Ahmad, R. Ismail, and S. A. Hamid, "Mucous Layer Effects towards Nasal Airflow," presented at the 2012 International Conference on Biomedical Engineering (ICoBE), Penang, 2012.
[30] G. J. M. Garcia, N. Bailie, D. A. Martins, and J. S. Kimbell, "Atrophic rhinitis: a CFD study of air conditioning in the nasal cavity," Journal of Applied Physiology, vol. 103, pp. 1082-1092, 2007.
[31] G. Xiong, J. Zhan, K. Zuo, J. Li, L. Rong, and G. Xu, "Numerical flow simulation in the post-endoscopic sinus surgery nasal cavity," Medical & Biological Engineering & Computing, vol. 46, pp. 1161-1167, 2008.
[32] K. Keyhani, P. W. Scherer, and M. M. Mozell, "A numerical model of nasal odorant transport for the analysis of human olfaction," J. Theor. Biol., vol. 186, pp. 279-301, 1997.
[33] R. G. Hooper, "Forced Inspiratory Nasal Flow-Volume Curves: A Simple Test of Nasal Airflow," Mayo Clinic Proceedings, vol. 76, pp. 990-994, 2001.
[34] R. Slack and G. Bates, "Functional Endoscopic Sinus Surgery," American Academy of Family Physicians, vol. 58, pp. 707-718, 1998.

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