Experimental and numerical investigations on the flow field inside pre- and post-surgery models of posterosuperior septectomy

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ABSTRACT
Three physiological functions of nasal breathing (air-conditioning, filtering and smelling) are closely related with airflow characteristics in the human nasal airway. Since fluid mechanical properties are heavily affected by the geometry of flow passage, the changes in anatomical shape of nasal cavity by disorders or surgical treatments alter the nasal resistance and functions of nose. In this article, the PIV measurement and numerical simulation has been conducted on the airflow in the pre- and post-surgery (posterosuperior septectomy by transnasal endoscopic surgery of anterocentral skull base) nasal cavity models. Two patients' cases were investigated: one with reduction of Creation of an accurate numerical cavity model from CT data is the key to analyze the flow inside of a complex passage by PIV and CFD. Dense CT (Computed Tomogram) data and careful treatment of model surface under the ENT doctor's advice provide more sophisticated cavity models for both PIV experiment and numerical simulation. The velocity fields in nasal cavity measured by PIV were compared with CFD results. We tried to find fluid mechanical properties that were correlated with functions of nose.

Keyword: PIV, CFD, Biomedical flow, Nasal cavity, Post-surgery model

INTRODUCTION

In addition to respiration, three other major physiological functions of nose can be described as air-conditioning, filtering and smelling. Detailed knowledge of airflow characteristics in nasal cavities is essential to understand the physiological and pathological aspects of nasal breathing. In our laboratory, there have been a series of experimental [1-3] investigations by PIV and numerical investigations [4-6] investigations on the nasal airflow in normal and simulated-surgery nasal cavity models under both constant and periodic flow conditions.

In order to remove the brain tumor where it locates in the anterocentral skull base, doctors may have surgery through the nasal cavity using endoscope by removing a part of the nasal septum, rather than by opening the cranium [9, 10] (**Fig. 1 a**). This operation method shows a tendency to increase due to the surgery accuracy caused by a clear view from endoscopy, shortened operation and recovery time, and lower riskiness compared to cranioplasty. However, there is a report that some particular endoscopic endonasal transsphenoidal surgery might cause hyposmia to the patients [11]. In this article, both experimental and numerical investigation has been conducted on the nasal cavity where posterosuperior part of the nasal septum has removed in the process of transnasal endoscopic surgery of anterocentral skull base. Two patients' cases (One with and the other without symptom of hyposmia after endonasal transsphenoidal surgery) were studied experimentally by PIV and numerically by CFD, as shown in **Fig.1**.

The buildings of an anatomically accurate 3D computer model and grid generation are indispensable for the successful numerical simulation of the flow inside human nasal cavity. This job cannot be performed successfully without close collaboration between engineers and medical doctors. With our experiences in the experimental [1-3] and numerical [4-6] investigations of nasal airflow in normal and abnormal nasal cavity models, using the 0.6mm-in-depth computed tomography (CT) data and a carefully treated model surface using this method, sophisticated physical and numerical models could be created in our laboratory.

Many desire outcome measurements in nasal surgery, but few can agree on the measuring tools yet. The existing objective tests such as rhinomanometry and acoustic rhinometry are not universally available or accepted. With the lack of knowledge on the correlation between symptoms and objective findings, standard criteria for diagnosis and expected outcomes of surgical treatments for nasal diseases have not been fully established. The use of computer-assisted measures, ranging from facial anthropometrics to nasal airflow modeling using CFD principles after validation by reliable experimental method such as PIV, is believed to be the next frontier in objective measures for diagnosis and nasal surgery outcome.

CREATION OF NASAL CAVITY MODELS

The building of an anatomically accurate 3D computer model is indispensable in the successful experimental and numerical investigations of the flow inside the human nasal cavity. Three dimensional computer models of nasal cavity were created using axial CT images with 0.625 mm thickness (LightSpeed 16; GE Medical Systems, Milwaukee, MI, USA) by established procedures in our lab [5, 7]. These CT images were acquired at the St. Mary's Hospital in Seoul as a part of routine clinical procedures.

From a set of 2D CT images, regions of nasal airway are segmented to be reconstructed as a 3D nasal airway model by using medical Image processing software such as Mimics (Materialize co., Ann Arbor, USA) (**Fig.2** left). A segmentation procedure for generating a 3D nasal airway model of a patient requires exquisite examination and deterministic process on CT images of the patient. Even an otolaryngologist with years of experiences needs several hours of work to completely build a 3D nasal airway model for a patient from his CT images. Such a hard and difficult procedure does not seem to be desired, if it would be applied to a patient-specific diagnosis and prognosis. It motivated our research to develop more productive and more convenient procedure for semi-automatic segmentation. Our method of segmentation, 3D model generation, simulation was based on the network based collaborative working environment (or CSCW, computer supported cooperative work) can be adopted (**Fig.2** right). It follows that medical doctors, computer scientists, and CFD researchers share CT images, 3D nasal airway models, and simulation results to work on surgery planning together from different places using the network based collaborative working environment [8].

Many investigators, who used Mimics and ICM-CFD (ANSYS Inc., USA) as a segmentation tool, experienced degrading resolution problem (decimation) occurring during the plugging the segmented 3D surface file (.STL) into the gird generation program (ICEM-CFD or Gambit, etc.). Recently, introduction of the Rapidform (INUS Tech. INC., Seoul, Korea) software resolved this problem [5, 7], as can be seen in **Fig.3,** improvements on the boundary shape and grid system was obvious. After considering both the convergence condition (**Fig. 3c**) and the computer cost, number of elements in the simulation model was chosen to be about 2,000,000 tetrahedral elements with five parallelepiped layers at near wall (**Fig.3b**).

EXPERIMENTAL AND NUMERICAL METHOD

To increase the resolution of image, a two times model of nasal cavity was used in PIV measurements. Experimental setup for PIV measurements is given as follows. A double-pulse Nd:Yag Laser (150 mJ/pulse, 2 mm laser sheet in thickness) was synchronized to a CCD camera (1600 × 1200 pixel resolution, LaVision Co.) by a trigger controller. A rectangular section (about 200 × 150 mm^2) is chosen as a test section by using a AF 50 mm F1.8 Nikkor Lens (set F5.6

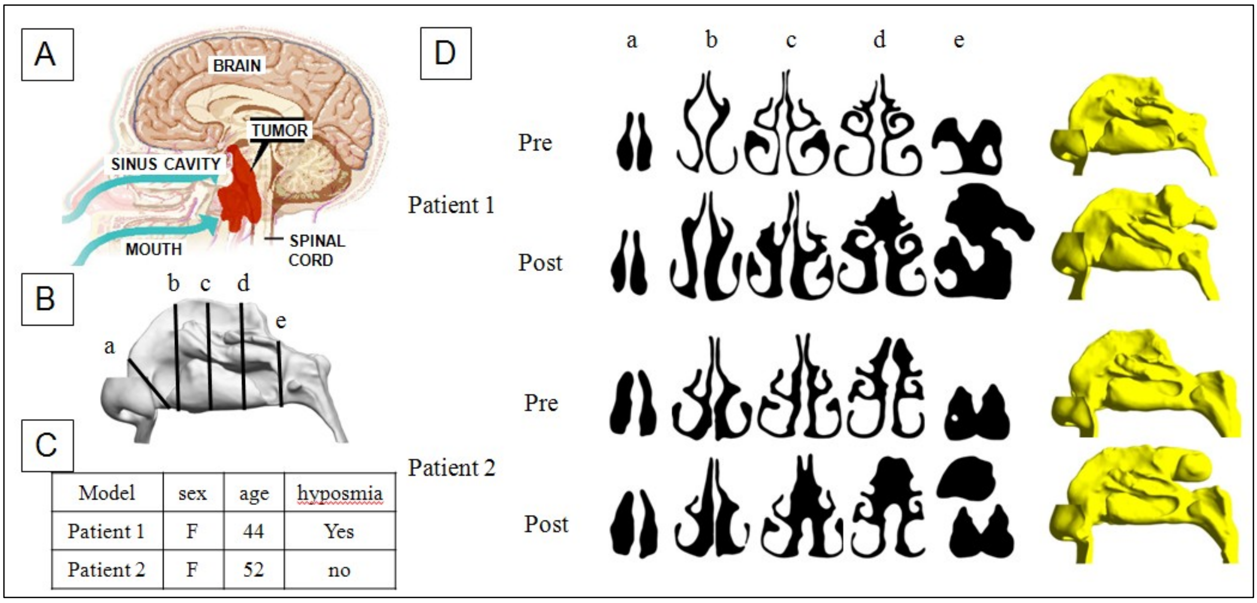


Figure 1 Pre- and Post-surgery nasal cavity models: a. Anatomy of endoscopic endonasal transsphenoidal surgery b. Five plane of coronal view c. patient report d. five coronal planes

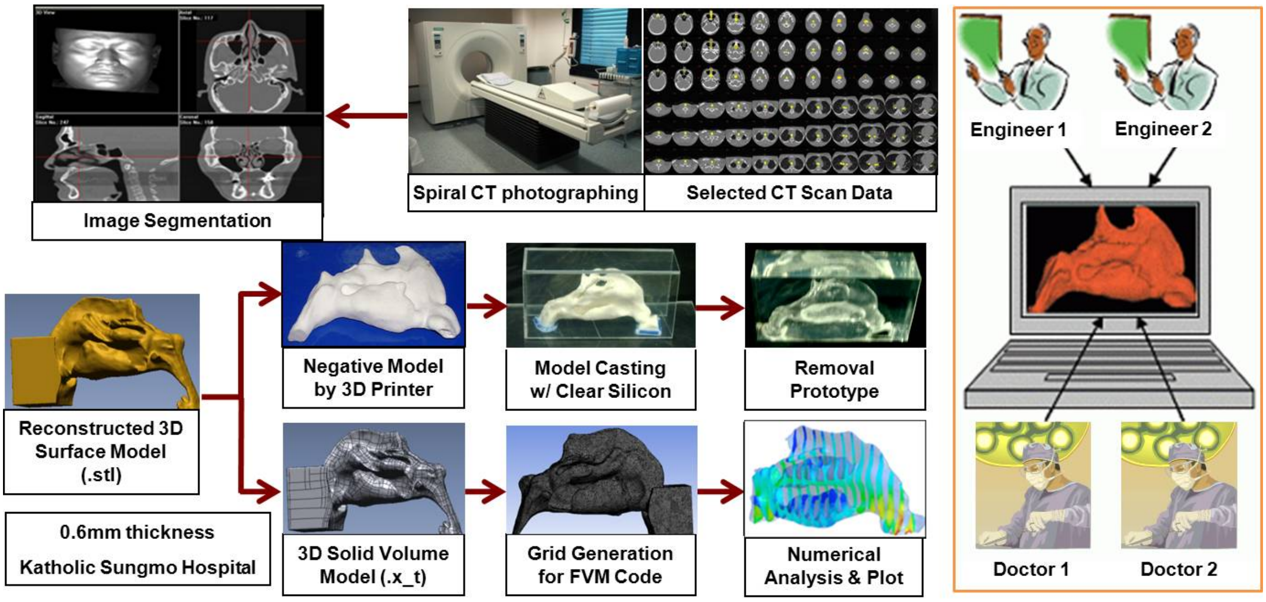
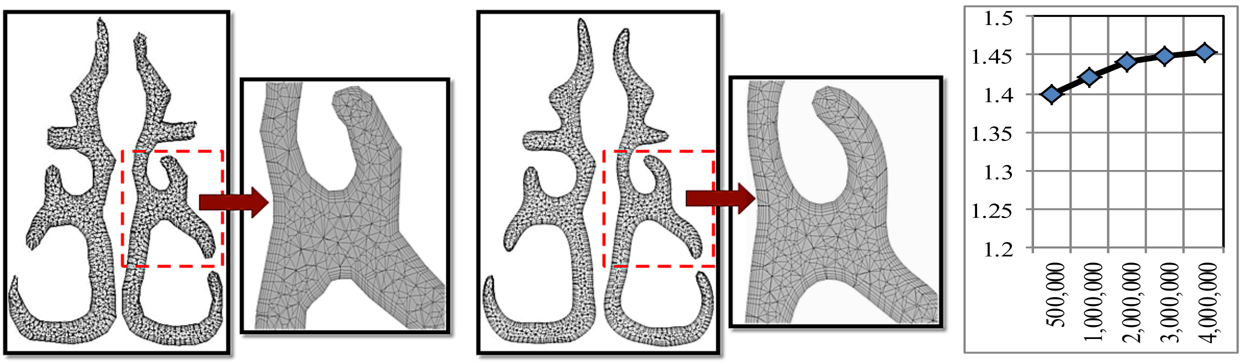


Figure 2 Procedure of creating numerical and experimental nasal cavity model (left [7]) **and Network based co-work system** (right)



(a) Past method (b) New method by using Rapidform (c) convergence test

Figure 3 Numerical grid generation in a sagittal plane and convergence test for area averaged velocity

in use) with a band-pass filter. The polyester particles (1.2 in density and 40 micrometer in diameter) are used as tracers. The flow rate used in this study corresponds to a resting respiratory flow rate in the real nose of 250 ml s^{-1}. In order to match the reflex of index of silicon model, a mixture of water and glycerin is used as working fluid. Since a mixture of water and glycerin (55:45 in volume, $\nu = 11.11 \times 10^{-6}\,m^2/s$, ρ=1170 kg/m^3, 20°C) is used as working fluid in PIV measurements, the Reynolds number must be equal to those of real air breathing condition to achieve the dynamic similarity. Reynolds Number was based on *U* (average velocity in the external nares) and *d* (hydraulic diameter of the external nares).

The continuity, Navier-Stokes equation, heat and passive scalar (moisture) transfer equations for incompressible are to be solved numerically. Flow properties are assumed to be constant.

$$\nabla \cdot \mathbf{U} = \mathbf{0} \tag{1}$$

$$\boldsymbol{\rho} \frac{\partial \mathbf{U}}{\partial \mathbf{t}} + \boldsymbol{\rho} \left(\mathbf{U} \cdot \nabla \right) \mathbf{U} = -\nabla \mathbf{p} + \boldsymbol{\mu}\, \nabla^2 \mathbf{U} \tag{2}$$

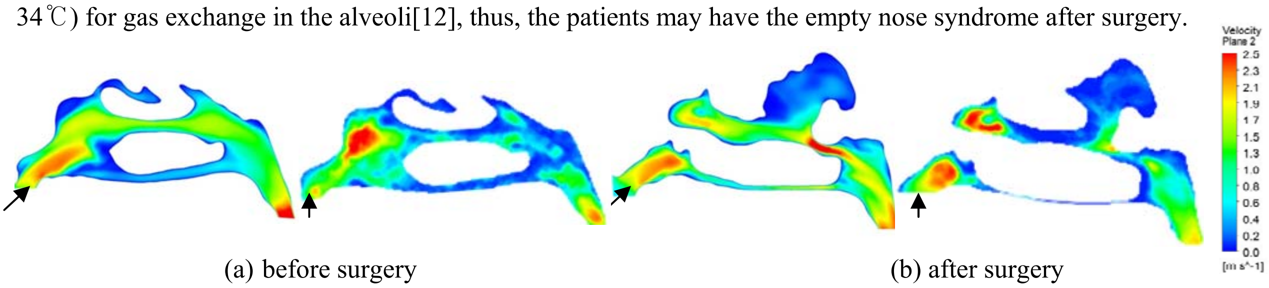
$$\frac{\partial \mathbf{T}}{\partial \mathbf{t}} + \left(\mathbf{U} \cdot \nabla \right) \mathbf{T} = \frac{\mathbf{k}}{\boldsymbol{\rho}\, \mathbf{c_p}} \nabla^2 \mathbf{T} + \Phi \tag{3}$$

$$\frac{\partial \mathbf{C_{H_2O}}}{\partial \mathbf{t}} + \left(\mathbf{U} \bullet \nabla \right) \mathbf{U} = \mathbf{D_{H_2O}}\, \nabla^2 \mathbf{C_{H_2O}} \tag{4}$$

The specific heat, c_p= 1004.4 J/kg/K, thermal conductivity of air, k =0.0261W/m/K. $\boldsymbol{C_{H2O}}$ is the water vapor concentration in air, the mass diffusivity of water vapor in air, $\boldsymbol{D_{H2O}} = 2.6\times10^{-5}\,m^2/s$. A commercial software package FLUENT (ANSYS Inc., USA) was used to investigate the flow physiology. Flow was assumed to be laminar. To know the correlation between the symptom of hyposmia and heat/water transfer, we also considered the temperature and water vapor concentration boundary condition on mucosal wall. The nostril side is defined as the opening boundary at room temperature 20°C and atmospheric pressure. At the throat side, a flow rate is applied to drive the flow in the cavities. Vapor concentration is assumed to be 100 % on the nasal wall due to the presence of mucus layer.

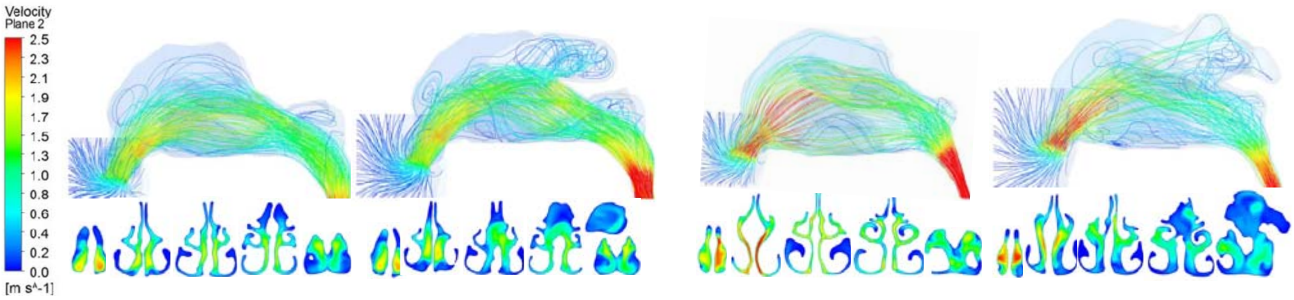
RESULTS AND DISCUSSION

Experimental and numerical results of velocity field on sagittal plane for pre- and post-surgery models are shown in Fig. 4, with the flow direction at external nostrils which is represented as arrows. The local region where maximum velocity occurs is similar, and the results are qualitatively in agreement. In the CFD results, due to widening of airway after surgery, the maximum velocity magnitude as well as pressure drop (Δp) decreased in post-surgery model as shown in **Fig. 5, 6a** respectively. However, the air temperature at the 'plane e'(at the end of septum) in the post-surgery model was much lower than that in the pre-surgery model (**Fig. 6 b**). This temperature is below the optimal condition (about 34℃) for gas exchange in the alveoli[12], thus, the patients may have the empty nose syndrome after surgery.



(a) before surgery (b) after surgery

Figure 4 Sagittal velocity distribution by CFD(left) and PIV(right) for pre- and post-surgery models



(a) A patient without hyposmia after surgery (b) A patient with hyposmia after surgery

Figure 5 Streamline and coronal velocity profile for pre- and post-surgery models for symptomatic and asymptomatic patients by CFD

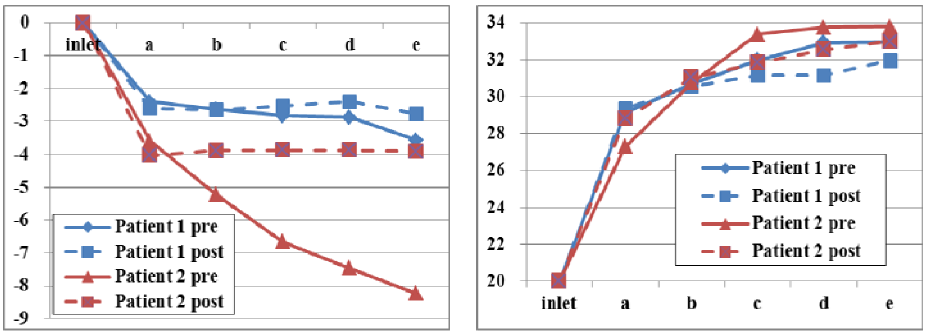


Figure 6 CFD results: Pressure drop (left), temperature (right) graph for Pre- and Post- surgery nasal cavity models

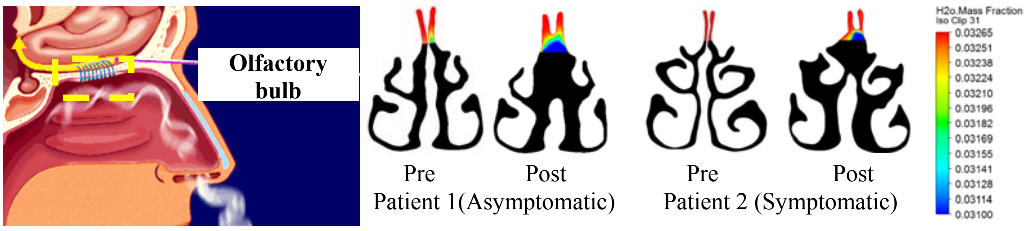


Figure 7 Location of olfactory bulb in the nasal cavity(left) and h_2o mass fraction in olfactory region(right)

Table 1 Summary of mechanical properties on both patients' Pre- and Post-surgery models

	Patient 1 (no symptom)		Patient 2 (hyposmia symptom)	
	Pre-surgery	Post-surgery	Pre-surgery	Post-surgery
Surface Area	0.0238515 m^2	0.023696 m^2	0.0235693 m^2	0.0253503 m^2
Nasal volume	6.31342e-5 m^3	8.49065e-5 m^3	4.4533e-5 m^3	9.18717e-5 m^3
Wall Heat Flux	161.883 W	161.323 W	183.835 W	159.651 W
Local relative humidity in olfactory region	0.032576 g/m^3 99.8%	0.032215 g/m^3 98.7%	0.03265 g/m^3 100%	0.03171 g/m^3 97.1%

It is known that the sense of smell is stimulated in the upper airway (shown in **Fig.7**) where olfactory cells and bulb are located. Also, relative humidity is known as one factor which can influence on the olfactory sense. Therefore, local relative humidity in olfaction region can be the one of the criteria on diagnosis of hyposmia or anosmia. In the **Table 1**, the amount of wall heat flux decreased in the both patients' post-surgery model compared to those in pre-surgery model, but noticeably, the decrement in the model for patient 2 (hyposmia symptom) was more prominent than that for the patient 1 (no symptom). Similarly, the larger amount of local relative humidity in olfactory region fell in the post-surgery for patient 2 compared to those for patient 1(**Fig. 7** right**, Table 1**), which might explain the reason of symptom of hyposmia from the standpoint of fluid mechanical properties.

SUMMARY

The procedure to create anatomically correct physical and numerical models was established by introducing the network based communication system and semi-automatic segmentation procedure. Airflows inside pre- and post-surgery (posterosuperior septectomy in endoscopic endonasal transsphenoidal surgery) models were investigated by PIV and CFD. Velocity, temperature and humidity fields were strongly dependent on the changes in geometrical structure of the cavity models. Although this surgery results in reduction of the flow resistance, it may weaken the local air-conditioning ability in olfactory region, which may cause the severe reduction in olfactory function. We propose that with the use of CFD to find correlation between reduction in function of nose and fluid dynamical properties such as heat and humidity transfer. These results may contribute to establish the patient-specific, objective, tools for diagnosis and prognosis.

ACKNOWLEDGMENT

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (2011-0028942).

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