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Nasal airflows in deformed nasal cavity models

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Abstract: Several studies have utilized physical models of the healthy nasal cavity to investigate the relationship between nasal anatomy and airflow. With our experiences of experimental investigations on nasal airflows in normal and abnormal nasal cavity models, we are going to deal with the topic that may contribute to the diagnosis and treatment of nasal diseases. In this paper, airflows in the normal and artificially deformed models, which simulate surgical treatment, are investigated experimentally by PIV. High-resolution CT data and careful surface rendering of computational model with the help of the ENT doctor provide more sophisticated nasal cavity models. The CBC PIV (Correlation Based Correction PIV) algorithm with window offset is used for PIV flow analysis. Average and RMS distributions in sagittal and coronal sections are obtained for inspiratory and expiratory nasal airflows. Comparisons in nasal airflows for both normal and deformed cases are also appreciated. In case of simulations of surgical operations, velocity and RMS distributions in coronal section changes locally, this may cause some difficulties in physiologic functions of noses and may hurt mucosal surface.

Keywords: PIV, Nasal Cavity Model, CT data, RP(Rapid Prototyping)

1. Introduction

Among the fluid flows inside human body, we are to investigate the airflow during respiration. The knowledge on airflow characteristics in nasal cavity is essential to understand the physiologic and pathologic aspects in nasal breathing. Therefore, many medical and biomechanical researches have investigated on the nasal airflow. Several studies have utilized physical models of the nasal cavity in an effort to understand the relationship between nasal anatomy and the distribution of inspired and expired airflow (Scherer et al. 1989, Hess et al. 1992). Hopkins et al (2000) and Kelly et al. (2000), recently established a procedure to construct a transparent rectangular box containing a model of the nasal cavity for PIV measurement by combination of the RP (Rapid Prototyping) and the curing of clear silicone. Creating the accurate transparent flow passages is essential to analyzing the flow inward a complex flow passage by PIV. We improved procedure to produce the better cavity model with high-resolution CT scan data and the surface rendering (Kim and Son 2002) and extended this work to deal with airflow in an abnormal nasal cavity with adenoid vegetation and asymmetry (Kim and Son 2004a, Kim and Son 2004b).

These experiences stimulate the further extension of these works to the simulation of medical treatments. An ENT doctor cannot try multiple choices of surgical operations to a patient with an otorhinolaryngological disease. But, we can do simulations of those by PIV experiments with the normal nasal cavity model and its variations, each of those representing the cavity models of different post-surgical conditions. A nasal airway is mainly composed of three hooked passages (inferior, middle, superior airways) enclosed by nasal septum and inferior, middle, superior turbinate.

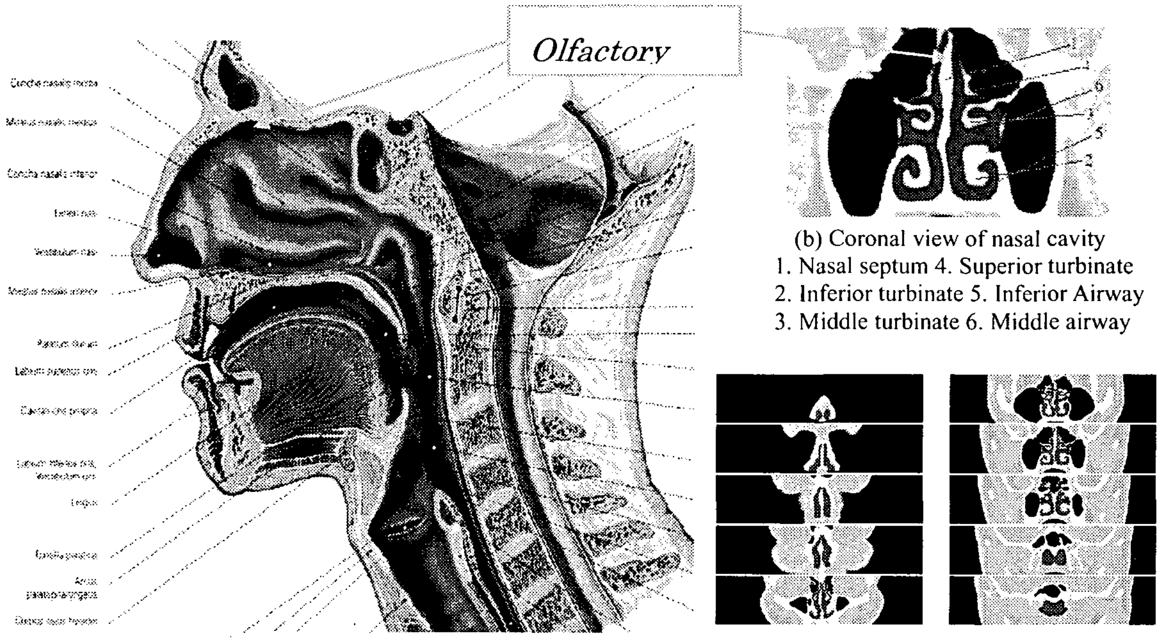
The surgical removal of middle turbinate is chosen as the first example. (Kim and Son 2004c) Now this is expended to deal with the removal of inferior turbinate in this article. To check the validity of the paradigm used in these works, investigation on one more nasal cavity model of different person is conducted. A two times model of one half healthy nasal cavity was made and then its variations are made as follows; Among the procedures to produce the cavity model, three dimensional computer model from CT data is altered to mimic the surgical removal of some part of middle turbinate by the ENT doctor. With this computer model, nasal cavity models of six surgical conditions are created by same procedures for the normal one.

The tomographic PIV technique is introduced to investigate complex flow structure in nasal cavity. As nasal airway is composed of thin hooky passages, nasal airflow is nearly 2 directional except the region near the nasal valve. Thirty-four sagittal sections with 1 mm in thickness are investigated by PIV measurements. The CBC PIV algorithm (Hart 2000) with window offset (64*64 to 32*32) is used for vector searching in PIV analysis (Kim 2001). The three dimensional reconstruction of velocity fields gives insights on flow characteristics of each model. Movie files of sequential velocity distribution of coronal plane show the changes in the direction of mainstream in different nasal models. Velocity and RMS distributions in coronal section changes locally; this may cause some difficulties in physiologic function of noses and may hurt nasal mucosa.

The paradigm established in this paper can be applied to many kinds of otorhinolaryngological diseases and is believed to contribute to the diagnosis and treatment including surgical operation of nasal diseases

2. Flow passage inside the nasal cavity and nasal anatomy

A brief nasal anatomy, related with the analysis on nasal airflow, is depicted in Fig. 1. Two nasal cavities are separated by a nasal septum. A nasal airway is mainly composed of three hooked passages (inferior, middle, superior airway) enclosed by nasal septum and inferior, middle, superior conchas. In physiologic state, one of nasal cavities is used alternately for a period of hours. Therefore only one nasal cavity model is used in experiments. Most flow rates are believed to pass through the middle and inferior airways. Usually, parts of the passage can be blocked or bent by disease or injury. Therefore, CT scan data of a Korean adult after rendering in computer model is



(b) Coronal view of nasal cavity
1. Nasal septum 4. Superior turbinate
2. Inferior turbinate 5. Inferior Airway
3. Middle turbinate 6. Middle airway

(a) Sagittal view of nasal anatomy

(c) Selected Coronal CT scan data

Fig. 1 Nasal anatomy and flow passage in nasal cavity

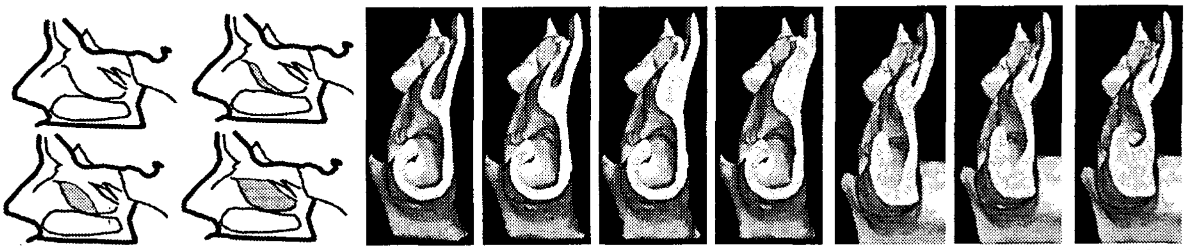

Normal Model 1 Model 2 Model 3 Model 4 Model 5 Model 6

Fig. 2 Sagittal (left) and Coronal (right) views of normal cavity model and its 6 variants

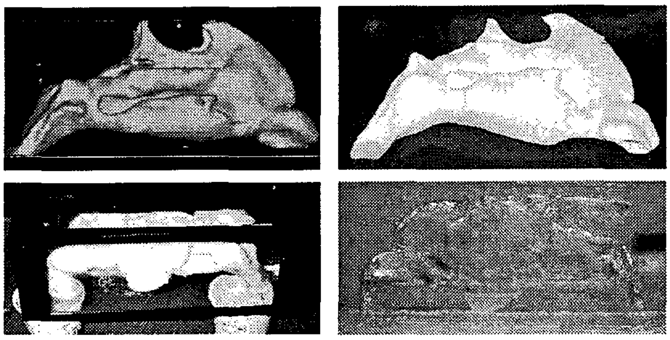


Figure 3. Creation procedures of cavity model

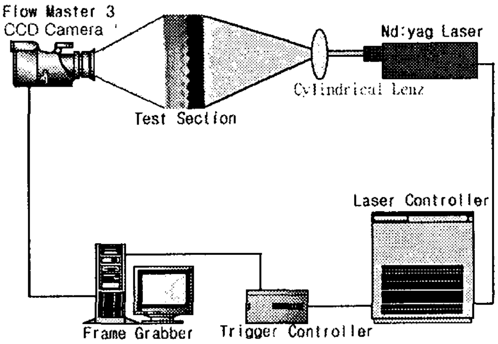


Figure 4. Set-up for PIV measurements

adopted as the normal nasal cavity model. Irrelevant parts, such as sinuses, are not included to reduce the optical noise. From this model, we made 3 variants with partial removals of turbinate as shown in Fig. 2.

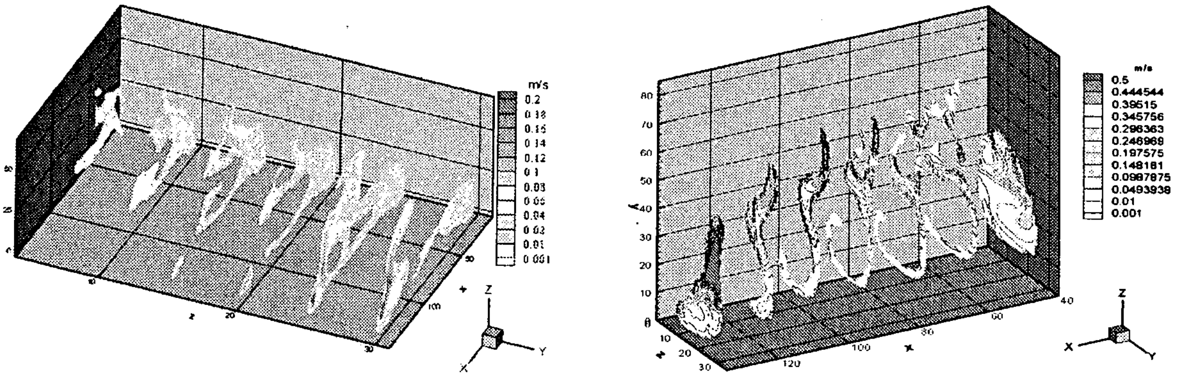
3. Creation of flow passage and experimentation

Creating an accurate transparent flow passage is essential to analyze the flow inward a complex flow passage by PIV. The key to producing a geometrically complex flow passage suitable for PIV is the recent availability of a rapid prototyping machine and water-soluble material for a negative model. Rapid prototyping is a well-accepted method for quickly generating replicate prototypes from computer files including CT scan data. The procedure of creating flow passages is summarized as follows [7];

At first, a solid computer model for building the replicate model is created from coronal CT scan data (Somatom plus 4, Siemens. Co., 0.6mm scan rate) of Korean adults (Fig.1c). Then, a replicate prototype of the nasal cavity, made of water-soluble cornstarch, is created by a RP machine (Z Co. MA. USA). This prototype is suspended in a rectangular Plexiglas box. Then, clear silicone is poured around the prototype carefully. After the silicone has been cured in an oven, the cornstarch prototype is removed with cold water. Finally, a rectangular box containing the form of the nasal cavity can be made. To remove the difference in the index of reflectance, the mixture of water and glycerin is used as a working fluid, as shown in Fig.3.

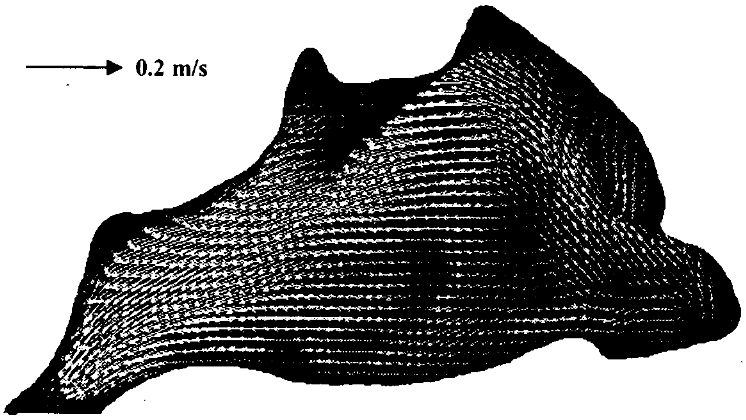
Due to the large amount of CT scan data (166 scan with 0.6mm increment) and the careful surface rendering, more sophisticated nasal cavity model can be made and used in this article. Irrelevant parts, such as sphenoid sinus, are removed to reduce the optical noise.

A 2X model of one healthy nasal cavity was made by the aforementioned procedure. Its variations are made as follows; Among the procedure, three dimensional computer model from CT data (upper left photo in Fig.3) is altered to mimic the surgical removal of some part of middle turbinate by ENT doctors. Experimental Setup for PIV measurements is given in Fig.4 [7]. A double pulse Nd:Yag Laser (150 mJ/pulse, 2mm Laser Sheet thickness) is synchronized to a CCD camera (1280 × 1024 pixel resolution, LaVision Co. Flow-Master 3) by a Trigger Controller. A rectangular section (about 200*150mm^2) is chosen as a test section by using a AF 50mm F1.8 Nikkor Lens (set F2.8 in use) with a band-pass filter. The polyester particles (1.02 in density and 80

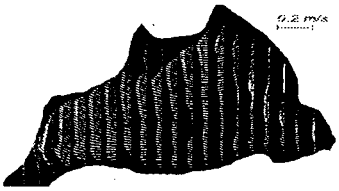


(a) Sagittal velocity data form PIV Measurements (b) Coronal data from 3D reconstructed data

Figure 5. Coronal data from 3D reconstruction of tomographic PIV measurements in Sagittal planes

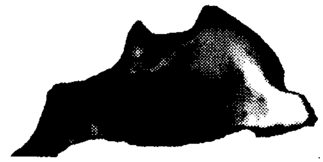


(a) Average velocity plot (1024 vector set)



(b) Reduced average velocity

(c) Mean streamline



(d) RMS distribution

Figure 6. PIV results of resting inspiration in sagittal plane near septum (Normal nasal cavity)

micrometer in diameter) are used as tracers.

From these tomographic data of 34 sagittal planes, a 3 dimensional velocity data set can be reconstructed and 128 coronal section data, familiar to ENT doctors, are produced. (Fig.5)

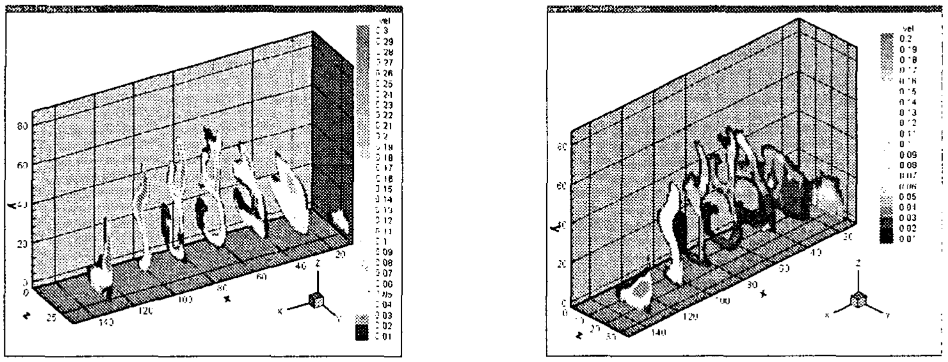
4. Results and Discussion

An average velocity distribution in a flow passage near the nasal septum for a normal nasal cavity are obtained from a 1024 velocity vector set by PIV analysis, as shown in Fig.6 (Kim and Son 2002). Larger RMS values, equivalent to larger heat and mass transfer, can be seen at the level of the anterior part of the middle airway, and the flow rate was highest at the middle airway. Velocity distributions in coronal planes provide better visualization for the direction of main stream as shown in Fig.7, where colored levels denote amplitude of average and RMS velocities.

For the case of the simulation of surgical operation, since the parts removed by the simulative surgery are fully 3 dimensional, coronal velocity data reconstructed by tomographic PIV results of 34 sagittal planes is the only choice to understand and compare the flow characteristics of each model.

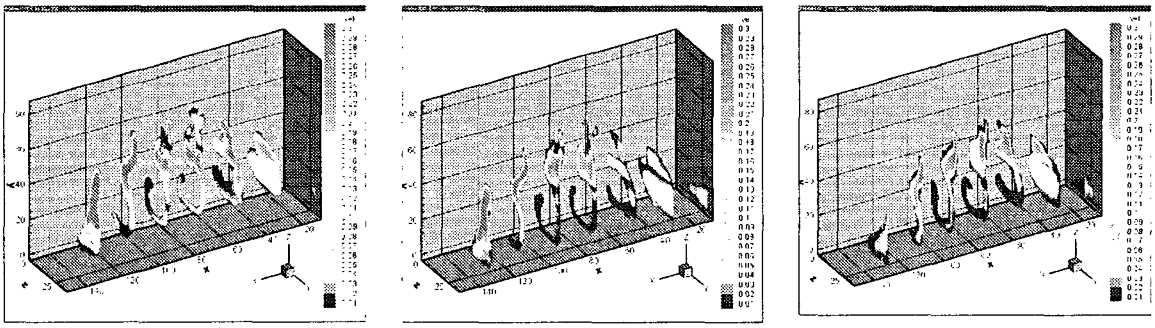
Fig.7 depicts the coronal velocity for normal and 6 variant nasal cavity models. The direction of mainstream is altered by partial removal of turbinate. Animated movie gives the better understanding on the flow characteristics for each model. Comparing with the normal nasal cavity case, RMS distributions of its variants, shown in Fig.8, change locally and this may cause some difficulties in physiologic function of noses and may hurt nasal mucosa. Moreover, RMS values of all partially removed models increase, which may cause the hardness to breath and change the physiologic function of nose. Relatively speaking, the anterior half middle turbinectomized model (Model3) and Model 6 show better feature as far as concerning RMS distribution in selected coronal sections. To apply this result in real surgical situation, more comprehensive investigations with full data are needed.

Further investigations on the medical decisions in detail are needed with joint work with medical doctor in the area of the otolaryngology. But we can expect that these quantitative flow data will contribute to the diagnosis and treatment including surgical operation of nasal diseases.

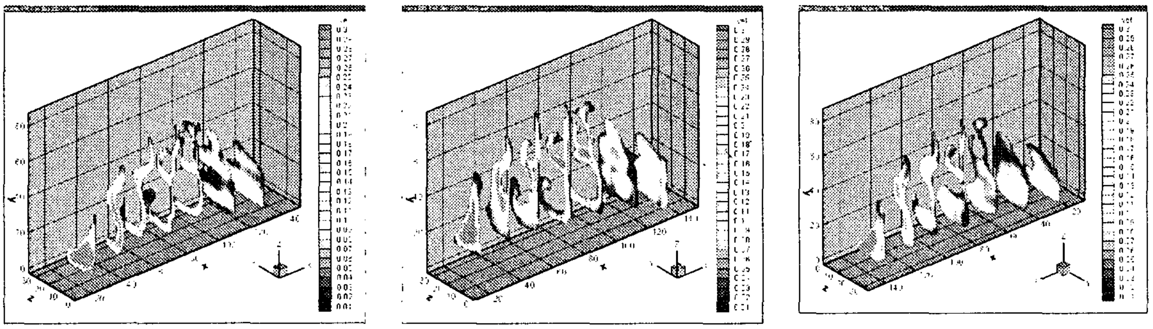


(a) Average velocity distribution (b) RMS velocity distribution

Figure 7. PIV Results of Average and RMS Velocity in Coronal Sections (Normal model)

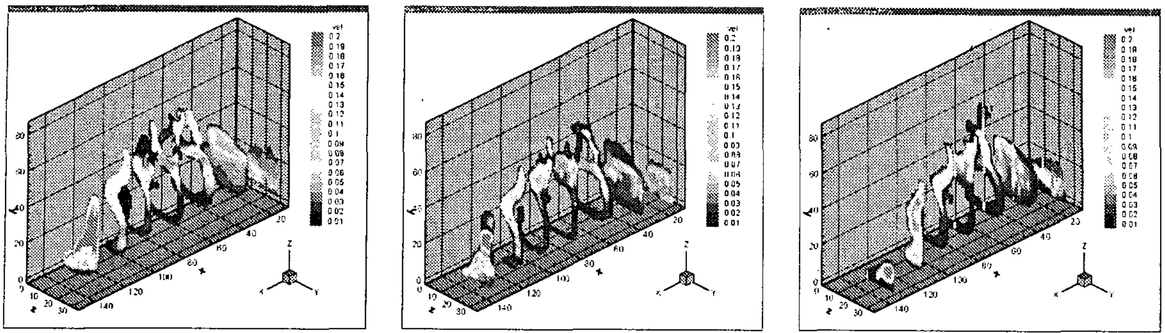


(a) Model 1 (b) Model 2 (c) Model 3

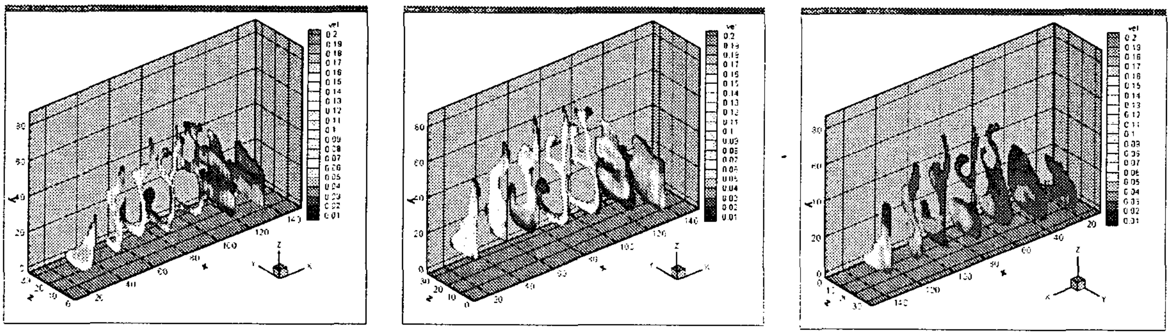


(d) Model 4 (e) Model 5 (f) Model 6

Figure 8. PIV Results of Average Velocity in Coronal Sections (Deformed Models)



(a) Model 1 (b) Model 2 (c) Model 3



(d) Model 4 (e) Model 5 (f) Model 6

Figure 9. PIV Results of RMS Velocity in Coronal Sections (Deformed Models)

6. Conclusion

We have shown the typical application of PIV measurements to biomedical problem in the area of the otolaryngology. The procedure to create the sophisticated nasal cavity models is established, that results in obtaining the reliability of PIV results. Through the 3 dimensionally reconstructed quantitative data of nasal airflow for a normal and 6 variants, which simulate surgical operation, the relationship between the nasal airflow and nasal anatomy and physiology can be investigated more seriously. With the paradigm in this article, PIV measurement can contribute to the diagnosis and treatment including medical operation of nasal diseases and is believed to do an active role in the area of biomedical engineering. This methodology can be extended to investigate any other flow problems inside body like the circulatory

References

Hart D.P., "PIV error correction", Experiments in Fluids 29 (2000) 13.

Hess, M.M., Lampercht, J., Horlitz, S. "Experimentelle Untersuchung der Strombahnen in der Nasenhaupthoehle des Menschen am Nasen-Modell", Laryngo-Rhino-Otol. 71 (1992) 468

Kelly, J.T., Prasad, A.K., Wexler, A.S. "Detailed flow patterns in nasal cavity", J. Appl. Physiol. 89 (2000) 323

Kim, S.K., Son, Y.R. "An Experimental Study of Developing and Fully Developed Flows in a wavy Channel by PIV", KSME Int'l J. 15,(12) (2001) 1853

Kim, S.K., Son, Y.R., "Particle Image Velocimetry Measurements in Nasal Airflow", Trans. KSME B, 26(6) (2002) 566

Kim, S.K., Jung, S.K., "An Investigation on airflow in disordered nasal cavity and it's corrected models by tomographic PIV", Meas. Sci. Technol. 15 (2004a) 1090

Kim, S.K., Son, Y.R., "Investigation on Airflows in Abnormal Nasal Cavity with Adenoid Vegetation by Particle Image Velocimetry", KSME Int'l J. 18(10) (2004b)

Hopkins, L.M., Kelly, J.T., Wexler, A.S., Prasad, A.K. "Particle image velocimetry measurements in complex geometries", Exp. Fluids 29 (2000) 91

Kelly, J.T., Prasad, A.K., Wexler, A.S. "Detailed flow patterns in nasal cavity", J. Appl. Physiol. 89, (2000) 323