Investigation on Airflows in Abnormal Nasal Cavity with Adenoid Vegetation by Particle Image Velocimetry

Sung Kyun Kim*
Department of Mechanical Engineering, Konkuk University, #1 Whayang-dong Kwanggin-gu Seoul, 143-701, Korea
Young Rak Son
GraduateSchool of Mechanical Engineering, Konkuk University, Seoul, Korea

Knowledgeof airflow characteristics in nasal cavity is essential to understand the physiological and pathological aspects of nasal breathing. Several studies have utilizedphysical models of the healthy nasal cavity to investigate the relationship between nasal anatomy and airflow. Since the final goal of these works is their contribution to the diagnosisand treatment of nasal diseases, the next step on this topic is naturally studies for disordered nasal cavities. In this paper, as the first application, airflows in the normal and abnormal nasal cavities with adenoid vegetation are investigated experimentally by PIV, and comparisons of both cases are appreciated. Dense CT data and careful treatment of model surface under the ENT doctor's advice provide more sophisticatedcavity model. The CBC PIV algorithm with window offset is used for PIV flow analysis. Average and RMS distributions are obtained for inspirational and expirational nasal airflows. Airflow characteristics that are related with the abnormalities in nasal cavity are presented.

Key Words : Nasal Airflow, Adenoid Vegetation, PIV (Particle Image Velocimetry), Computed Tomogram (CT)

1. Introduction

Knowledge of airflow characteristics in nasal cavities is essential to investigate the mechanisms of their main physiological functions, such as filtration, air conditioning, and olfaction. Therefore, many medical and biomechanical researches have investigated the nasal airflow. Several studies have utilizedphysical models of the healthy nasal cavity in an effort to understand the relationship between nasal anatomy and the distribution of inspired and expired airflow.

Among others, Scherer et al. (1989) measured airflow rate in a 20X solid modelby the hot-wire anemometer (HWA). Hess et al. (1992) reported flow visualization results of dye-streak photos. Their model was made of clear silicone through casting of a death body. Hopkins et al. (2000) recently established a procedure to construct a transparent rectangular box containing a model of the nasal cavity for PIV measurement by the Rapid Prototyping (RP) and the curing of clear silicone. But the geometry of their model looks unrealistic and the model was mounted upside down.

In our previous papers (Kim, 2002 ; Kim and Son, 2003), airflow and pressure drop in a healthy Korean person's nasal cavity were investigated and PIV results of instantaneous, the mean and RMS velocities in case of a normal cavity were reported and compared with published ones. A 2X enlarged model of one half a nasal cavity was made for PIV measurement. An actual size model

* Corresponding Author,
E-mail : sungkim@konkuk.ac.kr
TEL : +82-2-450-3472; **FAX** : +82-2-3436-0540
Department of Mechanical Engineering, Konkuk University, #1 Whayang-dong Kwanggin-gu Seoul, 143-701, Korea. (Manuscript **Received** October 13, 2003; **Revised** June 14, 2004)

was made for pressure drop measurement.

Main procedure to make a cavity model in this paper followed Hopkins et al. 's one. Two major improvements to make a better model are given as following ; dense CT scandata (169 coronal views with 0.6mm thickness) and careful treatment of model surface under an ENT doctor's advice. The CBC algorithm with window offset (64×64 to 32×32) is used for vector searching in PIV analysis (Kim, 2001).

Among otorhinolaryngological diseases for children, the adenoid vegetation is one of the most frequent to cause the breath difficulty. The adenoid vegetation (AV from now on), a swollen lymph tissue at the upper part of a pharynx, usually appears at the age of 3～4, and disappears at the age of 14～15. Symptoms of this disease are the tendency of mouth breathing caused by a blocked nose, incorrect pronunciation, etc. Martino et al. (1998) investigated the pressure drops in inspiration and expiration in both healthy persons and the cases of adenoid vegetation.

The main purpose of this paper is to help ENT doctors in curing AV through the investigation on airflow characteristics by PIV measurement and the pressure drop measurements in normal and abnormal Korean nasal cavities with AV. Since the creation of accurate transparent flow passages is essential to analyze the flow in a complex flow passage by PIV, we established the procedure for creating an accurate nasal cavity model.

The normal nasal cavity model is deformed to have 50% and 70% AV through the surface rendering on the three dimensional computer reconstruction images of CT data. We conduct PIV measurements on these two models and, for the first time, produce quantitative data which are compared with data of a normal cavity model.

We also conduct the pressure measurements with varying flow rates and opening ratios. The pressure measurement data show good agreements in trend with Martino et al. (1998)'s results. We conjectured that AV exceeding 60% causes a rapid increase in pressure drop between nares and pharynx, which may narrow the uncertainty in decision for medical surgery (generally known as 50-70%). We also find that the laminar flow persists until flow rate reaches to 400ml/s in inspiration. The PIV results confirm this fact through the comparison of flow characteristics and RMS quantitiesnear the nasopharynx between models of 50% and 70% AV.

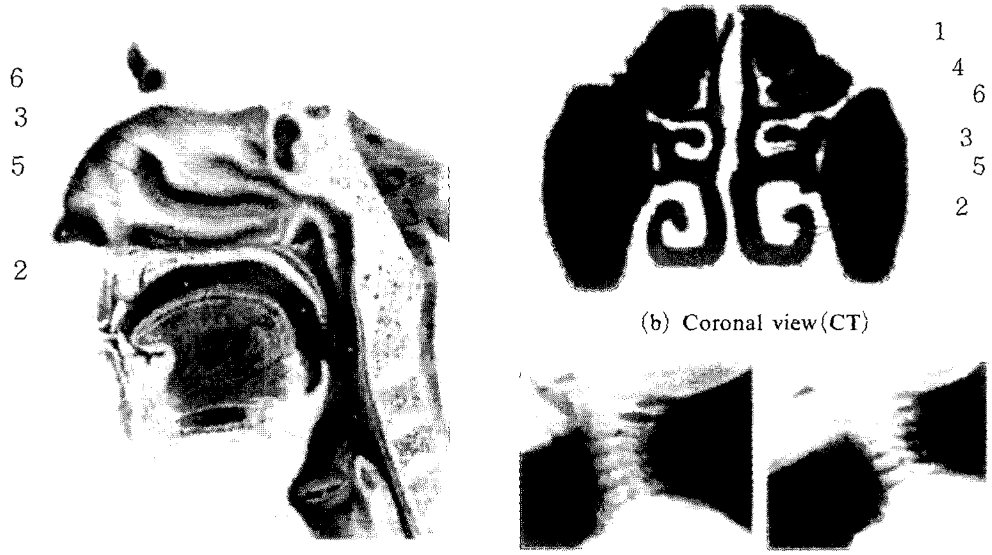
2. Nasal Anatomy and Physiology

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 the state of relaxation, one of the nasal cavities is used alternately for a period of hours. Most flow rates are believed to pass through the middle and inferior airways.

Kelly et al. (2000) summarized the previous works on flow direction and flow rates in nasal cavities of western people. Though there were various opinions in the direction of mainstream-depending on each nasal cavity model (Swift and Proctor, 1977 ; Girardin et al., 1983 ; Schreck et al., 1993 ; Hahn et al., 1993 ; Keyhani et al., 1995 ; Park et al., 1997), recent results (Subramaniam et al., 1998 ; Kelly et al., 2000) show that the main stream passes the middle and lower airway and there is very little flow in the olfactory slit (upper airway) and miatuses (tail parts of hooked airways).

Usually, parts of the passage can be blocked or bent by disease or injury. Therefore, having consulted with an otorhinolaryngologist, CT scan data of a Korean adult after modification in computer model is adopted as the nasal cavity model. Irrelevant parts, such as the sphenoid sinus, are removed to reduce the optical noise. The AV is a swollen lymph tissue at the upper part of a pharynx located at the end of nasal cavity, as shown in Fig. 1(c)

Martino et al. (1998) reported both the pressure drop measurements and dye streak visualization of three nasal cavity models with AV (38, 62, 83% in area block ratio). Pressure drop increased sharply in between 62% and 83%.



(b) Coronal view(CT)

(a) Ssgittal view (c) Normal(left) & AV(right)

Fig. 1 Nasal Anatomy : 1. Nasal septum 2. Inferior concha 3. Middle concha 4. Superior concha 5. Inferior airway 6. Middle airway

3. Flow Passage and Experimentation

Creating accurate transparent flow passages is essential for analyzing 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 (Fig. 2. Di Martino et al., 1998 ; Hess et al., 1992) ; at first, a solid computer model for building the double-sized replicate model is created from dense coronal CT scan data (Somatom plus 4, Siemens Co., 0. 6mm scan rate) of Korean adults with and without AV. Then, RP machine (Z Co. MA. USA) produces a replicate prototype of the nasal, according to CT data. It is made of water-soluble cornstarch. 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

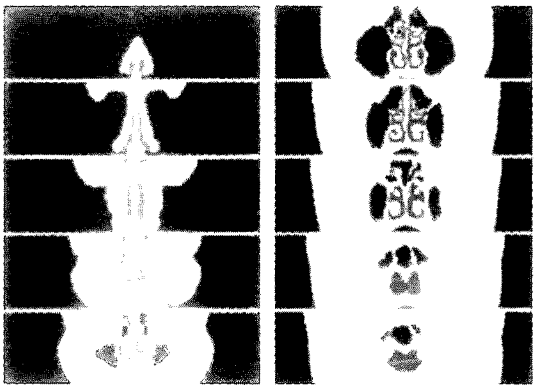


Fig. 2 Selected Coronal CT scan data of a male nasal passage(Normal person)

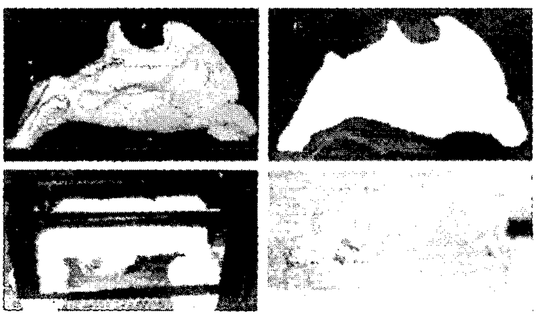


Fig. 3 Creation procedures of nasal cavity model

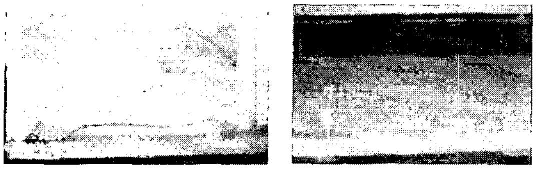


Fig. 4 Photo of model filled with water (Left) and one with Water-Glycerol mixture (Right)

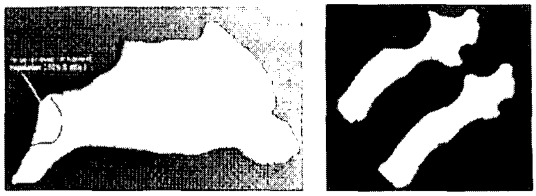
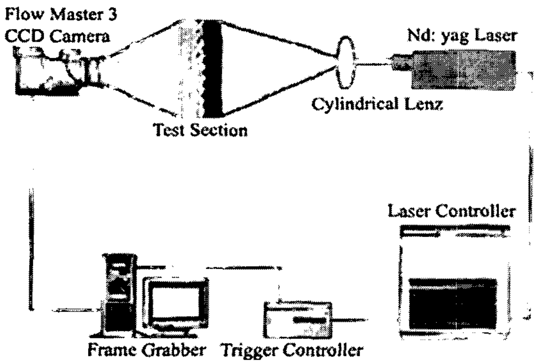
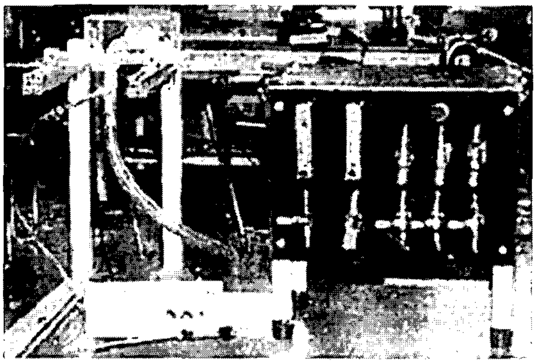


Fig. 5 Adenoid Vegetation : X-ray photo (Right)

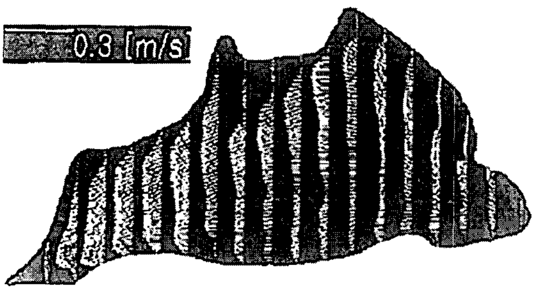


(a) PIV Measurements

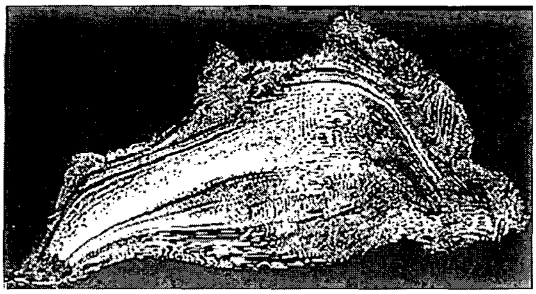


(b) Pressure Drop Measurements

Fig. 6 Experimental Set-ups

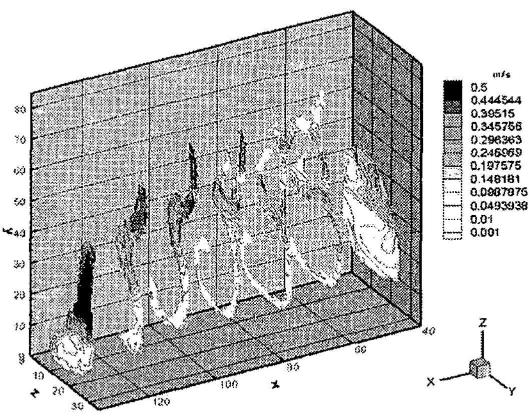


(a) Average Velocity Plot (1024 images)



(b) Mean streamline

(c) RMS distribution



(d) Coronal Velocity Distribution (nares left)

Fig. 7 PIV Results of resting inspiration at concha (Normal): Flow rate of 125ml/sec.

the flow passage of the nasal cavity can be made. A fine sand paper is used to smooth small steps on the surface of the model, resulting from RP procedure, under medical doctor's advice. 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. 4. For a flow passage of a nasal cavity with AV, portions of the pharynx, 50% and 70% in cross sectional area, are removed from the replicate model, as shown in Fig. 5. Figure 6 (a) is a schem- atic diagram of PIV apparatus. A double pulse Nd : Yag Laser (SPECTRON Co., 150 mJ/pulse) is synchronized to LaVision Flow Master 3 CCD camera (LaVision Co., 1280 1024 pixel resolution) with 105mm Nikkor Micro Lens by a Trigger Controller. The polyester particles (Glass Bead-Hollow's part#900890, 8-12 micrometer in diameter) are used as tracers.

A CBC PIV algorithm with window shifting (64×64 to 32×32 pixels in window size) is adapted. Adjacent interrogation spots of a final stage were overlapped by 50%. Since the nasal airway is composed of thin hooked passages, except at near the nasal valve region, velocity is almost two-dimensional. Therefore, two-dimensio-nal and Replicate models of 50% and 70%.

PIV is adequate in the sagittal plane. Coronal velocity distribution, with which medical doctors are familiar, is obtained from the three dimensional reconstruction of 34 sagittal PIV results. (Fig. 7d) An apparatus for measurement for the pressure drop depicts in Fig. 6 (b). A 1 : 1 nasal cavity model is used and a pair of nares is open. The nasopharynx is connected to a fan or a vacuum pump for inspiration and expiration respectively.

4. Results and Discussion

An average velocity distribution in a flow passage near the nasal septum and conchas for a healthy Koreanadult is obtained from 1024 velocity vector set by PIV analysis as shown in Fig. 7 (Kim, 2003). Coronal Velocity distributions are obtained from 3D reconstruction of 34 Sagittal PIV Measurements.

While the main stream passed through the middle and inferior airways and there showed high airspeed in the inferior airway in the majority of the previous results for westernpeople (Swift and Proctor, 1977 ; Girardin et al., 1983 ; Schreck et al., 1993 ; Hahn et al., 1993 ; Keyhani et al., 1995 ; Park et al., 1997 ; Subramaniam et al., 1998 ; Kelly et al., 2000), the main stream passes through the middle airway and there is relatively small airspeed in the inferior airway for Korean people in this paper. One possible reason is the dependency on the nasal cavity model, more precisely the characteristics of the individual person's nasal cavity (Some results like Swift and Proctor (1977)). The other possibility may be due to the difference in nasal anatomy between the western people and Korean people, especially the shape of the entrance (Nares). In the approaching direction of airflow at the nares for the Korean is upward, while that of the western is inclined. It is horizontal in the Hopkins et al. (2000)'s nasal cavity model.

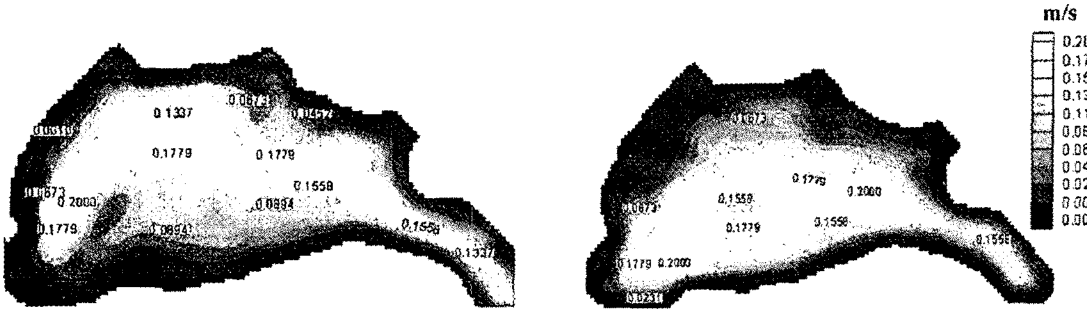
The quantitative data for the cases of 50% and 70% AV are given in Figs. 8-11. Comparing with the normal case, the direction of the main stream in inspiration for the case of 50% AV is almost identical except at the region near nasopharynx in inspiration, but that for the case of 70% AV moves upward (Figs. 8a, 11a and 9a, 11c).

This may cause difficulties or deficiencies in the physiological functions of exchanging heat and moisture due to the rare distribution of capillary blood vessels in the upper parts of the airway. In expiration, the main stream passes through the middle and lower airways (Figs. 8b and 9b), which is parallel to the Martino et al. (1998)'s observation. In both inspiration and expiration, higher velocities and intensive concentration of higher RMS value near a swollen lymph tissue are observed.

A closer look at the nasopharynx in inspiration, as shown in Figs. 12-13, leads to following conjecture ; in case of 50% cases, blocked nose caused by excessive pressure drop is not so severe, but, in 70% case, flow resistance increases rapidly. It can be explained by flow re-circulations (while there was one re-circulating region in 50% AV case, there were two in the 70% AV case, as indicated by red arrows in Fig. 13.), and remarkable increases in RMS quantities in the throat. These differences in flow characteristicsfor 50%

(a) Resting inspiration (b) Resting expiration

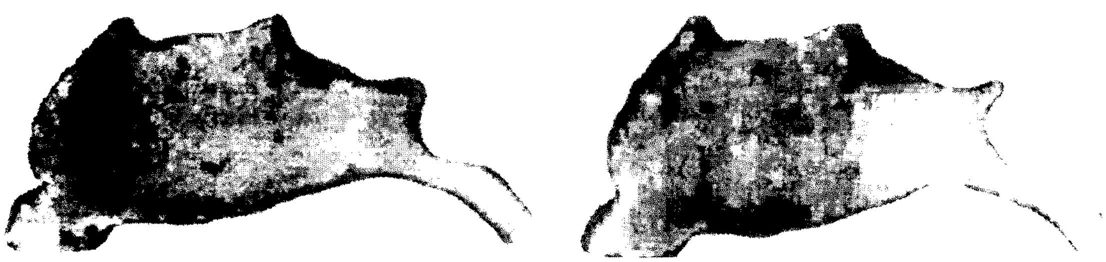
Fig. 8 Mean velocity near nasal septum (50% AV)



(a) Resting inspiration (b) Resting expiration

Fig. 9 Mean velocity near nasal septum (70% AV)

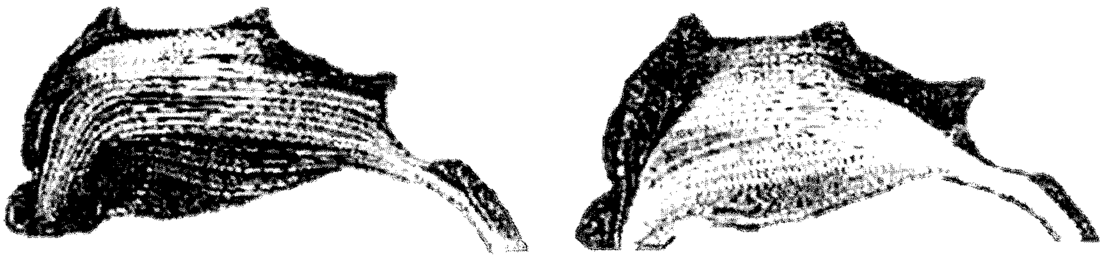
(a) Inspiration (50%) (b) Expiration (50%)



(c) Inspiration (70%) (d) Expiration (70%)

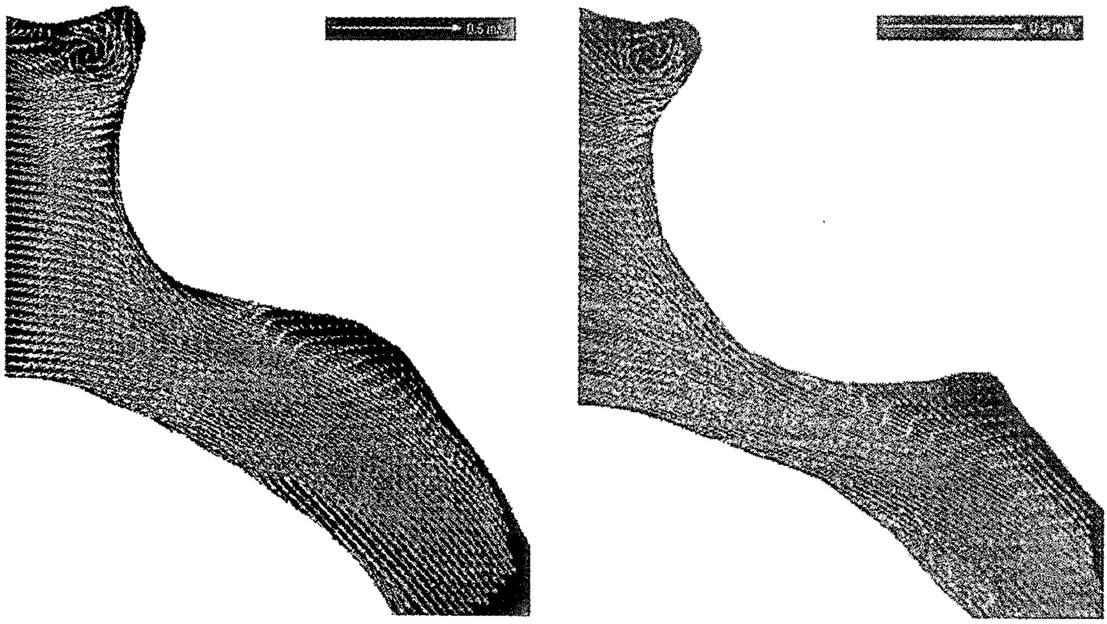
Fig. 10 RMS velocity distribution near nasal septum : Flow rate of 125ml/sec.

(a) Inspiration(50% AV) (b) Expiration(50% AV)



(c) Inspiration(70% AV) (d) Expiration(70% AV)

Fig. 11 Average streamlines near nasal septum

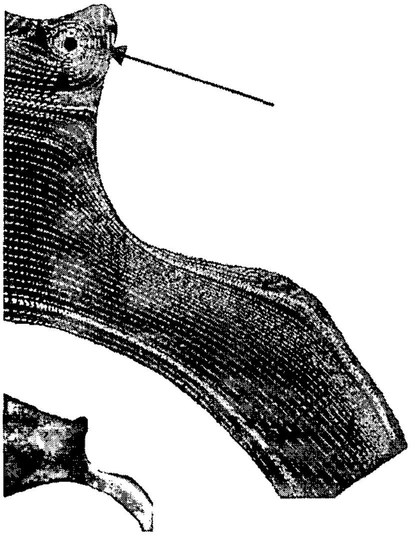


(a) Inspiration(50% AV) (b) Inspiration(70% AV)

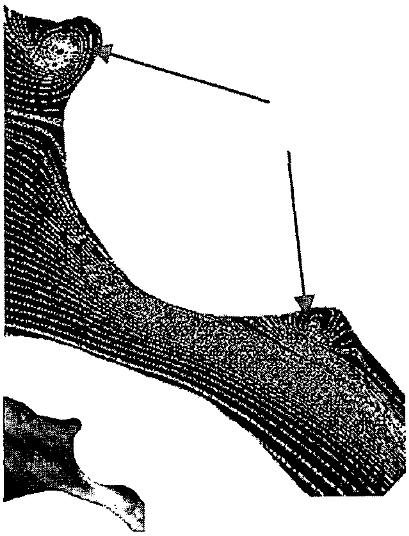
Fig. 12 PIV Results of resting inspiration at throat

and 70% AV are related with the sharp increase in pressure drop (flow resistance) between nares and nasopharynx in this range.

We obtained the pressure drop results for 4 nasal cavity models with AV (40, 50, 60, 70% in block ratio) to find the critical block ratio (CBL). From the results depict in Fig. 14, CBL lies between 60% and 70%. The ENT doctor's decision for surgical operation for removing AV is generally in between 50% and 70% AV. The results in this paper may narrow this uncertainty to 60~70% and it is believed that more experi-



(a) Inspiration (50% AV)

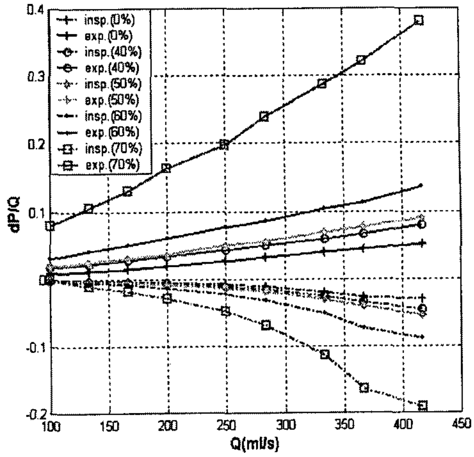


(b) Inspiration (70% AV)

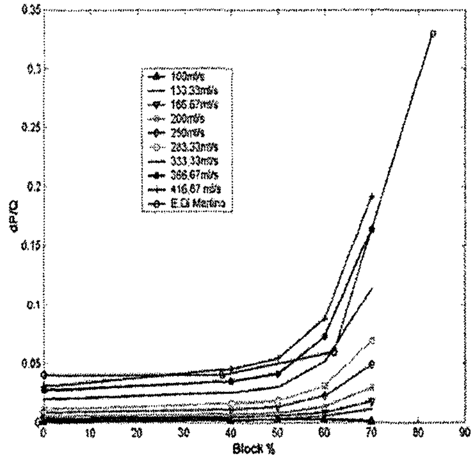
Fig. 13 Streamline (large) and RMS distribution (small)

ments can narrow further this gap.

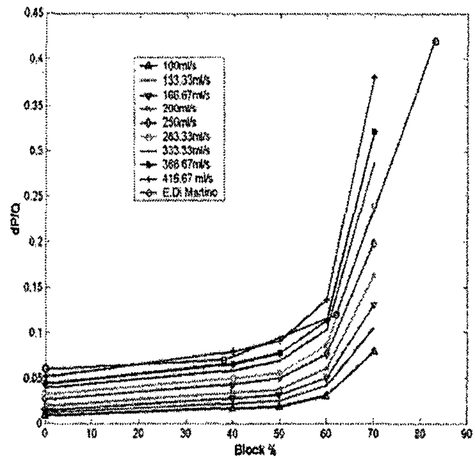
The similarity in pressure drop curves with va rying flow rate and block-ratio shows that flow characteristics before nasopharyns are almostidentical with those of the normal cavity case. From the linear variation of Δp with respect to Q, laminar flow persists until flow rate reaches up to 400ml/s for inspiration in the model with and without AV. This fact agrees well with the results of Chometon et al. (2000).



(a) Pressure drop with varying Flow rate (Q)



(b) Pressure drop with varying block ratio for inspiration



(c) Pressure drop with varying block ratio for expiration

Fig. 14 Pressure drop between nares and throat

5. Conclusion

The nasal airflows in a normal and a diseased (Adenoid Vegetation) nasal cavity for Korean are measured quantitatively by using PIV technique. A procedure for creating accurate transparent flow passages with complex geometry is established. PIV analysis with CBC algorithm provides the reliable quantitative data for medical and bioengineering applications. From results of both PIV and Pressure drop measurement, comparing with the normal case, flow characteristics in abnormal cavity with Adenoid Vegetation are almost identical except the region near nasopharynx in inspiration. During inspiration period, airflow in the throat accelerates due to swollen lymph tissue, and flow resistance in this area is increased. In case adenoid vegetation is about 50%, this phenomenon is not so severe, but at 70%, the phenomenon becomes prominent. The evidence can be found in PIV results of flow characteristics and RMS quantities. Results of pressure drop between nares and nasopharynx confirm this fact.

PIV measurements for the other volume rate cases of AV will illuminate the flow characteristics of airflow for this disease, which greatly helps an ENT doctor's diagnosis and surgical treatment of this disease.

The paradigmestablished in this paper can be applied to many kinds of otorhinolaryngological diseases and is believed to contribute to the diagnosis and treatment including medical operation of nasal diseases.

Acknowledgment

This work was supported by Grant No. 2000-1-30400-002-3 from the Basic Research Program of the Korea Science and Engineering Foundation, Republic of Korea

References

Bockholt, U., Mlynski, G., Mueller, W., 2000, "Rhinosurgical Therapy Planning via Endonasal Airflow Simulation," Computer Aided Surgery, Vol. 5, pp. 175~179.

Chometon, F., Gillieron, P. Laurent, J., Ebbo, D., Kos-man, F., Lecomte, F., Sorrel-Dejerine, N., 2000, "Aerod-ynamics of Nasal Airways with Application to Obstruction," Proc. FLUCOME 2000, Canada.

Di Martino, E., Mlynski, G., Mlynski, B., 1998, "Einf-luss der Adenoidhyperplasie auf die Nasale Atemstroemung," Larygo-Rhino-Otol., Vol. 77, pp. 272~274.

Girardin, M., Bilgen, E., Arbour, P., 1983, "Experimental Study of Velocity Fields in a Human Nasal Fossa by Laser Anemometry," Ann. Otol. Rhinol. Laryngol., Vol. 92, pp. 231~236.

Hahn, I., Scherer, P. W., Mozell, M. M., 1993, "Velocity profiles measured for airflow through a large-scale model of the human nasal cavity," J. Appl. Physiol., Vol. 75, pp. 2273~2287.

Hess, M. M., Lampercht, J., Horlitz, S., 1992, "Experimentelle Untersuchung der Strombahnen in der Nasenhaupthoehle des Menschen am Nasen-Modell," Laryngo-Rhino-Otol., Vol. 71, pp. 468~471.

Hopkins, L. M., Kelly, J. T., Wexler, A. S., Prasad, A. K., 2000, "Particle Image Velocimetry Measurements in Complex Geometries," Exp. Fluids, Vol. 29, pp. 91~95.

Kelly, J. T., Prasad, A. K., Wexler, A. S., (2000) Detailed flow patterns in nasal cavity, J. Appl. Physiol. Vol. 89, pp. 323~337.

Keyhani, K., Scherer, P. W., Mozell, M. M., 1995, "Numerical Simulation of Airflow in the Human Nasal Cavity," J. Biomech. Engin., Vol. 117, pp. 429~441.

Kim, S. K., 2001, "An Experimental Investigation on Flow Field in a Pipe with Sinusoidally Wavy Surface by PIV," KSME Int'l J., Vol. 15, No. 12, pp. 566~569.

Kim, S. K., Son, Y. R., 2002, "Particle Image Velocimetry Measurements in Nasal Airflow," Trans. KSME B, Vol. 26, No. 6, pp. 566~569.

Kim, S. K., Son, Y. R., 2003, "An Investigation on Airflow in Abnormal Nasal Cavity by PIV," Pros. PSFVIP4, Shamonix, F4095.

Park, K. I., Brucker, C., Limberg, W., 1997, "Experimental Study of Velocity Fields in a

Model of Human Nasal Cavity by PIV," Proc. 7th Int'l. Conf. Laser Anemometry Advance & Appl.

Scherer, P. W., Hahn, I. I., Mozell, M. M., 1989, "The Biophysics of Nasal Airflow," Otol. Clinics N. Ame., Vol. 22, No. 2, April, pp. 265~278.

Schreck, S., Sullivan K. J., Ho, C. M., Chang, H. K., 1993, "Correlations Between Flow Resistance and Geometry in a Model of the Human Nose," J. Appl. Physiol., Vol. 75, pp. 1767~1775.

Subramaniam R. P., Richardson, R. B., Morgan, K. T., Kimbell, J. S., 1998, "Computational Fluid Dynamics Simulations of Inspiratory Airflow in the Human Nose and Nasopharynx," Inhal. Toxicol., Vol. 10, pp. 473~502

Swift, D. L. and Proctor, D. F., 1977, "Access of air to the Respiratory Tract," Respiratory Defence Mechanisms : Part I, New York : Dekker, pp. 63~93.