Digital particle image velocimetry studies of nasal airflow

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Abstract
Understanding the properties of airflow in the nasal cavity is essential to understanding physiologic and pathologic aspects of nasal breathing. Many attempts have been made to evaluate nasal airflow patterns using the best possible analytical methods available at the time. Recently, digital particle image velocimetry (DPIV) and computational fluid dynamic methods have been applied to this area. Digital PIV is an experimental method used to evaluate airflow in an accurately reproduced transparent model of the nasal cavity. In this review, use of the DPIV procedure in the study of nasal airflow, airflow patterns in quiet respiration, and changes to airflow after modification of the nasal turbinates are reviewed, along with aspects of the DPIV technique and the future role of DPIV in this field of research.

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1. Introduction

To understand nasal functions such as humidification, filtration, temperature control of inspired air, and olfaction, knowledge of nasal airflow properties is important. Many attempts have been made to evaluate nasal airflow patterns using the most up-to-date techniques available at a particular time in question. Using the same principle that the movement of dust particles can be recognized in a sliver of sunlight passing through a window, so too does the technique of particle image velocimetry (PIV) enable the measurement fluid velocity in a flow passage constructed using optically transparent materials (Adrian, 1991). In this way, the flow is seeded with tracer particles and is illuminated with a sheet of laser light. Two- or three-dimensional velocities within the illuminated plane are calculated with post processing after two subsequent positions of the particle are recorded. Digital PIV (DPIV) is the digital counterpart of the PIV technique (Willert and Gharib, 1991), where digitally recorded video images are analyzed computationally. While there was one difficulty in applying this technique to complex flow passages such as the nasal cavity and thereby to replicate these structures with optically transparent materials, this problem was overcome using the rapid prototyping method and water-soluble materials for negative models (Hopkins et al., 2000).

1.1. Studies of nasal airflow

In 1882 Paulsen first described inspiratory airflow in the nose, with air rising fairly vertically along the bridge of the nose toward the anterior end of the middle turbinate, where it is deflected and passes between the middle turbinate and the septum towards the posterior end of the inferior turbinate and the choana (Uddströmer, 1940). Thereafter, many investigators performed airflow experiments using cadavers as models or using other materials (Uddströmer, 1940). From the late 1930s onwards, experimental models were created from the nasal casts of cadavers and nasal airflow was examined with various kinds of methods, such as cigar smoke (Tonndorf, 1939), smoke (Proetz, 1951), an angle meter (Proctor, 1966), dye injection (Swift and Proctor, 1977), laser-Doppler velocimetry (Girardin et al., 1983), radioactive Xenon gas (Hornung et al., 1987) or aerosolized water particles (Simmen et al., 1999). The models made from the cadavers have inherent limitations associated with the postmortem shrinkage of soft tissue or the use of flat transparent nasal septa for visualization, meaning that more accurate and/or enhanced size models that reproduce actual conditions are required.

In the early 1990s, nasal cavity models were created using magnetic resonance imaging (MRI) or computed tomography (CT) images. Three times (Schreck et al., 1993) or 20 times (Hahn et al., 1993) scale models of the nasal cavity were made using clear plastic or Styrofoam slabs. Enlarged coronal images of the nasal airway, taken from normal subjects after decongestion of the nasal cavities (or not), were used as templates to cut clear plastic or Styrofoam slabs. The slabs were glued together serially to produce enlarged nasal cavity models, and flow measured by using a hot anemometer or a hot film anemometer.

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Since the traditional forms of flow visualization, such as hot wire anemometer and laser-Doppler velocimetry, could no longer satisfy the needs of modern research on flow dynamics, where flow features must be quantified instantaneously, the PIV method was developed to measure velocity fields non-intrusively and instantaneously (Huang, 1994). The DPIV method was applied to the schematic anatomic model of the nasal cavity (Park et al., 1997), an anatomically accurate nasal cavity model based on CT images (Kelly et al., 2000). Hopkins et al. recently established a procedure to construct a transparent rectangular box containing a X2 model of the nasal cavity for PIV measurement using a combination of the rapid prototyping method and the curing of clear silicone (Hopkins et al., 2000). Creating the accurate transparent flow passages is essential to analyzing by PIV flow inside the complex flow passage. These procedures were improved to produce the nasal cavity model using high-resolution CT scan data in the "digital imaging and communications in medicine" (DICOM) file format and surface rendering procedures (Kim and Son, 2002; Kim and Haw, 2004b). An amended method was applied to evaluate the change of airflow after various kinds of middle turbinectomies (Kim and Chung, 2004a), as well as patterns of nasal flow during the respiratory cycle (Chung et al., 2006). However, difficulties exist to apply DPIV methods to the many kinds of experimental models representing normal and abnormal characteristics of the nasal cavities.

The numerical simulation method, also known as the computational fluid dynamics (CFD) method, was first applied to an analysis of airflow in the nasal valve area (Tarabichi and Fanous, 1993) and to the study of airflow in the nasal cavities (Keyhani et al., 1995). Since then, the CFD method has been applied to the study of nasal airflow (Hörschler et al., 2003; Weinhold and Mlynski, 2004; Ishikawa et al., 2006), the distribution of temperature (Lindemann et al., 2004, 2006), odorant solubility or transport (Kurtz et al., 2004; Zhao et al., 2004, 2006a), deposition of nanoparticles (Shi et al., 2006), pathologic conditions of the nasal cavity such as septal perforation (Grant et al., 2004; Pless et al., 2004; Ozlugedik et al., 2008), atrophic rhinitis (Garcia et al., 2007), and surgical conditions such as inferior turbinate reduction (Wexler et al., 2005), various kinds of turbinectomy (Lindemann et al., 2005b; Hörschler et al., 2006), polypectomy (Zhao et al., 2006b), and radical sinus surgery (Lindemann et al., 2005a).

Given that a comparison of the results of experimental methods including DPIV methods and CFD methods showed good agreement (Keyhani et al., 1995; Weinhold and Mlynski, 2004; Hörschler et al., 2006), nowadays CFD is more commonly applied in studies of nasal airflow, particularly where flow instability may arise, though CFD requires validation by the DPIV technique or other experimental methods.

2. Digital particle image velocimetry

2.1. What is digital particle image velocimetry?

One of the oldest techniques for studying velocities in a fluid is seeding particles into the fluid. When the tracer particles are small and their specific weight is close to that of the fluid, they will move locally with almost the same velocity as the fluid. Tracking the tracer particles will therefore give information about the local fluid movement. PIV is a basic method in fluid dynamics research that provides high spatial resolution in a two-dimensional slice of the flow (Adrian, 1991). It is usually a planar laser light sheet technique in which the light sheet is pulsed twice, and images of fine particles lying in the light sheet are recorded on a video camera or a photograph. The displacement of the particle images is measured in the plane of the image and used to determine the displacement of the particles in the flow. The most common way of measuring displacement is to divide the image plane into small interrogation spots and cross-correlate the images from two time exposures. Essentially a matrix of grey level values, comprising the pixel image intensity values in an interrogation region of the first image, is compared with the image matrix of the second image, to determine whether similar features are found in both images, and if so, their relative spatial displacement. Cross-correlation is used to determine whether the pattern of imaged particles in the interrogation region corresponds to a similar pattern in the second image. The magnitude of the correlation peak corresponds to how closely the patterns are associated, and the displacement of the correlation peak from the origin provides a best statistical estimate of the mean displacement of the associated patterns. Modern PIV processing techniques employ a range of techniques to maximize the accuracy and robustness of the correlation estimate, including correlation scaling and fitting, adaptive region size and image distortion.

Digital PIV is the digital counterpart of conventional laser speckle velocimetry (LSV) and the photographic PIV technique (Willert and Gharib, 1991). Because PIV and LSV rely on single images for flow velocity measurements, phase information is lost. This causes a directional ambiguity for each recovered velocity vector in the field. With the DPIV technique, digitally recorded video images are analyzed computationally, removing both the photographic and opto-mechanical processing steps inherent to PIV and LSV. The directional ambiguity associated with PIV or LSV is resolved by implementing local spatial cross-correlations between two sequential single-exposed particle images (Willert and Gharib, 1991). Experimental investigation of turbulent flows requires techniques that allow three-dimensional measurements with high spatial and temporal resolutions. There exist several variants of PIV to measure the three-dimensional (3D) flow velocity fields: Stereoscopic PIV (SPIV), Defocusing DPIV (DDPIV), Tomographic PIV (TPIV), and Holographic PIV (HPIV).

2.1.1. Recent developments in particle image velocimetry algorithms

Stereoscopic PIV enables the measurement of all three velocity components inside a relatively thicker light sheet. It is based on the principle of stereoscopic imaging that is well known from human eyesight—two cameras image the illuminated flow particles from different angles. The combination of both camera projections allows the reconstruction of the “real” particle displacement inside the measurement area and the evaluation of all three velocity components (Arroyo and Greated, 1991). Dual-plane SPIV is an extension of SPIV to cover a multi-plane or a panoramic view of a widened domain. The measurement system for this method is composed of two double pulse lasers, four charge-coupled device (CCD) cameras, a combination of optics, and a sophisticated synchronization unit to cover two planes. This procedure has been utilized to achieve three component velocity fields with SPIV temporal capability (Kähler and Kompenhans, 2000).

Defocusing DPIV is a method that uses the defocus principle to identify the 3D locations of seeded particles (Willert and Gharib, 1992). This technique was successfully applied to measuring the trajectories of bubbles in two-phase flow (Pereira et al., 2000). Particle Tracking Velocimetry (PTV) is the optimal technique to be used when the particles are sparsely distributed in the observation volume, while PIV is the method of choice when the particle density is high and the velocity gradients across the cross-correlation interrogation window are small. PIV is the preferred method in two-dimensional (2D) measurements. For 3D measurements, 3D PTV has also been presented (Pereira et al., 2006).
Tomographic PIV is an extension of the stereoscopic 3D concept and enables the instantaneous measurement of all three velocity components in a complete 3D measurement volume. It is based on the principle of tomographic volume reconstruction that is well known from MRI. Recordings of the 3D light intensity field of the illuminated particles are reconstructed from the images of four cameras viewing from different angles. Velocity vectors in the volume are computed by an iterative 3D cross-correlation technique using deformed interrogation volumes (Elsinga et al., 2006).

The last technique to be introduced is HPIV, which uses volume illumination and holographic recording procedures. The holographic concept is superior to the other methods since it can provide an instantaneous 3D field with high spatial resolution. However, current holography does not allow for the statistical collection of data and is limited to relatively simple flow configurations (Hinsch, 1995, 2002).

As the nasal cavity is composed of thin passages, nasal airflow is nearly 2D, with the exception of regions near the nasal valve and nasopharynx. Tomographic measurement by 2D DPIV is quite adequate in most regions of the nasal cavity; however, in the regions near the nasal valve and pharynx, where flow is 3D, new techniques such as SPIV, TPIV, and DDPIV are recommended.

2.2. Creation of nasal cavity model

2.2.1. Three-dimensional computer model from computed tomography data and rendering

Before the creation of actual PIV models or CFD analysis, experimental models of the nasal airways have to be computer generated. As mentioned in other reviews, the nasal cavity model can be an imaginary one or generated from cadaver characteristics or CT or MR imaging. Although many authors described models from CT or MR imaging as being anatomically accurate, not all of these represent the true nasal condition.

When we compare the patency of both nasal cavities, usually one side is wider than the other side due to the nasal cycle. Generally the wider side is selected because the manual segmentation is easier to perform for the wider side. When the width of the nasal airway is checked in coronal imaging without spraying decongestant, the width is similar from one side to the other and usually within 1–1.5 mm. If the nasal mucosa is de congested before taking the CT scan, the nasal airways become wider. However, for the creation of an experimental model to evaluate the physiology of nasal airflow, images taken without decongestion should be used.

When a computer-generated model of the nasal cavity is made, a decision of the margin between the airway lumen and the nasal mucosa is very difficult to make, especially when the thickness of the image slice is over 2.5 mm. Thus, for the basis of a model, it is recommended to use the data of axial image reconstructed to have slice thickness less than 1.25 mm. The margins of the nasal cavities vary significantly when the window width and levels are adjusted. This phenomenon may come from the presence of mucus on the surface of the nasal mucosa. Therefore, the trend is to make the nasal cavity wider such that the cavities take on the appearance of atrophic rhinitis. Compared to the automatic 3D reconstruction of the bone or the contrast media-enhanced vessels with clear-cut margins, automatic segmentation of the nasal cavity does not meet expectation as of now due to partial volume effect since the nasal cavity is relatively small and the margins are unclear. While the resolution of the axial image is high, resolution of images in reformatted coronal or sagittal planes may not be as high because the voxel is not a regular hexahedron, height being longer than the length. For this reason, after automatic segmentation with threshold level of brightness, the manual segmentation should be performed not only in axial images but also in coronal and sagittal images. Therefore, the anatomic and physiologic expertise of the researcher who performs the manual segmentation is important.

Another point to be considered concerns the extent of the nasal cavity model. Because the primary mechanical source of the respiration comes from the lung, the presence of the nasopharyngeal airway is important. It is recommended that enough space around the nasal vestibule is made so as to not change the direction of the inspiratory flow (Bailie et al., 2006).

2.2.2. Prototyping of the experimental model

The creation of a transparent rectangular box containing a nasal cavity model is essential for DPIV measurements to be made. To make a transparent nasal cavity flow model, a computer-modeled replica prototype is possible with the rapid prototyping technique and water-soluble material for a negative model (Hopkins et al., 2000). Rapid prototyping is a generic term for rapid production of a physical model replica. Usually the prototypes are filled with wax or cyanoacrylate to increase their strength and become insoluble. On the other hand, replicate prototypes of nasal cavities created using an RP machine from computer-generated models are made of water-soluble consolidated cornstarch and are brittle and porous. Such prototypes are then painted with water-soluble glue to seal the pores at the surface, making the surface smooth and improving strength. The treated negative replica is suspended in a rectangular Plexiglas box and is encased in transparent silicone. After the silicone is cured in an oven, the negative replica made from cornstarch is dissolved with cold water and a transparent experimental model containing the nasal cavity flow passage is created.

To ameliorate the distortion of light when light passes through the flow passage and the silicone model, the index of refraction of the clear silicone and the working fluid should be matched: to achieve this, a mixture of water and glycerin is used as the working fluid. When the refraction indices of the silicone and the working fluid are matched accurately the margin of the nasal cavity model in the silicone disappears completely, as does the distortion associated with a grid placed behind the model. Usually the optimal ratio between glycerol and water is 59% glycerol to 41% water by volume.

2.2.3. Experimental setup

Working fluids containing particles are pumped through the transparent model from the nasopharyngeal portion, maintaining an input angle of 90°. The vestibular portion is connected to a reservoir at an angle of about 60° to the horizontal floor of the nose (Swift and Proctor, 1977). The flow in the nasal airway is visualized with buoyant particles. As a tracer, glass spheres of diameter 60 μm (Hopkins et al., 2000) or polyvinyl globular particles (80 μm in diameter) (Kim and Chung, 2004a) are used. The tracer particles are illuminated twice in rapid succession by a pulsed sheet of laser light and the image recorded by CCD camera.

2.3. Validity of experimental setup

2.3.1. Constant flow-rate condition

Achieving dynamic similarity with real breathing conditions in an experimental setting using fluids requires that the created model is scaled by a factor n, so that Reynolds number for the two conditions is matched. The relationship is described as:

\[ Q_{\text{mix}} = n \frac{V_{\text{mix}}}{V_{\text{air}}} Q_{\text{air}} \]

where Q is the volumetric flow rate and \( \nu \) is the kinematic viscosity. The kinematic viscosity of the working fluid is 6.55 × 10⁻⁶ m²/s at 27.5°C (Hopkins et al., 2000) and that of the air is 16 × 10⁻⁶ m²/s. Therefore, a flow rate of 102 ml/s was used for a working fluid that simulated the volumetric flow rate of air (125 ml/s) at a typical rest-
2.3.2. Dynamic similarity for respiratory cycle

In an experiment evaluating the nasal airflow pattern during normal respiration (Chung et al., 2006), Reynolds number and the Womersley Number (frequency parameters) in the experimental model were matched with those numbers in a real situation for achieving dynamic similarity with real breathing, while taking into account the size of the model and the characteristics of the working fluid. The period of the inspiratory–expiratory cycle and the tidal volume of the piston pump that simulate the respiration should then be decided. For a twice-life-size nasal cavity model used for the DPIV technique, where one inspiratory–expiratory cycle was assumed to be 3 s, that cycle was 30 s in the model. The tidal volume of the nasal cavity model was calculated to 2060 ml, while that of the normal adult in one nasal cavity was assumed to be 250 ml.

2.4. How to present DPIV results

The speed, direction and the root mean square of the flow are obtained. The average velocity can be displayed in the form of a vector plot, mean streamline, velocity in selected lines, amplitude of velocity, isoline plot, and serial velocities, as well as the distribution of root mean square (RMS) velocity in the measuring plane (Fig. 1) and of the reconstructed image in the selected plane (Fig. 2). Pictures of these presentations, except reconstructed images in selected planes, usually show only a few typical planes, which are parallel to the septum. As such, it is difficult to understand the global form of the flow in the nasal cavity with these kinds of display methods. Therefore, the measured data are presented in the plane showing the area where most of the flow passes. According to Keyhani’s report, major flow is in the axial direction and secondary velocities were small in comparison with the axial

![Fig. 1](image1.png)

![Fig. 2](image2.png)
velocity through most of the main nasal passage (Keyhani et al., 1995). Therefore, data are collected and redisplayed in the coronal plane (Fig. 2). By these methods, a 3D pattern of flow in the nasal cavity can be visualized from 2D images. Coronal reconstruction of the mean velocity and RMS value were thus performed to show 3D results from 2D data (Kim and Chung, 2004a; Chung et al., 2006). Although the reconstructed image looks 3D, it only contains the 2D vector in the measuring planes. This limitation in display methods can also be applied to the 3 components of velocity data. If the images of the coronal plane are shown on video or computer, then the shape of the flow can be visualized as a movie or in animated form.

2.5. Limitations

As for other solid models, this method cannot imitate changes in soft tissue form during respiration given that experimental models are not as flexible as living tissue. Until now, qualitative rather than quantitative data have been obtained, making it difficult to evaluate the results statistically. Also, evaluation of the normal pattern of nasal airflow in different populations is difficult because making many DPIV models and taking measurements requires a great deal of time. Given that most studies to date have been performed with a small number of individuals, it remains to be seen how these results can be extrapolated to describe general properties of whole populations.

3. Normal nasal airflow

3.1. Nasal airflow under conditions of constant flow rate

Most studies to date on nasal airflow have been conducted under the condition of steady flow during inspiration or expiration, with the assumption that nasal airflow is quasi-steady, and that flow patterns observed during the constant flow rate phase would not change considerably with acceleration or deceleration of flow (Baille et al., 2006).

The highest linear velocity is noted in the valve area, while the main nasal airflow during quiet inspiration was found in the space between the middle meatus and the nasal septum in most early experiments (Tonndorf, 1939; Proetz, 1951; Proctor, 1966; Swift and Proctor, 1977; Simmen et al., 1999). In a DPIV-based study of nasal airflow applied to a nasal cavity model based on CT scans (Kelly et al., 2000; Kim and Chung, 2004a), similar results were found except for the main pathway of airflow in the nasal cavity proper. The highest velocity was noted in the nasal valve and relatively low flows were noted in the olfactory region and both meatus. Although the major portion of the airflow was found in the inferior airway in Kelly’s experiment, the main airflow was noted in the middle airway in our experiments (Fig. 2) (Kim and Chung, 2004a). Knowledge of the main airflow path in the nasal cavity is important when deciding on surgical methods for patients with nasal obstructions. The major disagreements remain on the main pathways of airflow in the nasal cavities. Connection of the flow horizontally to the vestibular portion of the experimental model in Kelly’s study might be responsible for that difference.

Similar disagreements can be noted from early experiments performed in this field (Uddströmmer, 1940), as well as in studies conducted using the CFD method in nasal cavity models based on MRI or CT scans. Different main airflow pathways were noted in each nasal cavity of the same person (Fig. 3) (Zhao et al., 2004) and the principal pathways were highly variable within many samples (Churchill et al., 2004). The main pathways are influenced by many factors such as ethnic origin and shape of the external nose, especially the axis of the vestibule. The main flow tract seems to be decided by the curved line which connects the inlet and outlet axes. Therefore, it can be assumed that, if the axis of the inlet in the vestibule portion or the axis of the outlet portion in the nasopharynx is horizontal to the nasal floor, the main flow will probably be noted in the inferior meatus (Grützenmacher et al., 2005).

The nasal cavity is composed of the nasal cavity proper and three meatus under the corresponding turbinates. The boundary of this area is not clearly defined in the real nasal cavity, but is located roughly around the inferior and middle airway without there being any definite margin. Therefore, how much of the flow passes through any specific area is difficult to calculate. This may be the reason that the inferior and middle airways are used in the description of nasal airflow.

At an airflow rate of 12.5 l/min, airflow in the nasal vestibule is usually laminar and changes to turbulent after it passes the valve area in cadaver models (Swift and Proctor, 1977; Girardin et al., 1983). Nasal airflow at a flow rate of 180 ml/s showed disturbed laminar flow in an experimental model derived from MRI images, though laminar-like flow is probably present in much of the nasal cavity during normal breathing (Hahn et al., 1993). The airflow was laminar for a simulated air flow rate of 125 ml/s in two DPIV studies (Kelly et al., 2000; Kim and Chung, 2004a). The widths of the nasal airways probably account for discrepancies between studies.

In relation to eddy turbulence in airflow during inspiration, two small eddies have been noted in front of the inferior turbinate and in the vestibule, while an eddy in the olfactory area suggested by other authors (Swift and Proctor, 1977) was not confirmed in DPIV studies (Kelly et al., 2000; Chung et al., 2006).

3.2. Nasal airflow during the respiratory cycle

The airflow pattern during normal quiet respiration was reported in coronal reconstructed images (Chung et al., 2006). The maximum velocity occurred in the valve area and the main flow stream occurred in the middle airway and middle meatus during inspiration (Fig. 4). The inspiratory flow passed through the upper
Fig. 4. Coronal reconstruction of mean velocity in the left nasal cavity. The maximum velocity occurred in the nasal valve area (C) and the main path of flow was in the middle airway during respiration. The velocity during inspiration (B, C, and D) is faster than that during expiration (F–I). (A) The beginning of inspiration; (B) in the middle of inspiratory acceleration; (C) at the maximum velocity; (D) in the middle of inspiratory deceleration; (E) during the change between inspiration and expiration; (F) at the maximum velocity during expiration; (G–I) during expiration (each letter in the respiratory flow curve [center box] represents the location of each image). The period of one cycle (A–I) was 30 s in the model, equivalent to the real period of 3 s. Modified from Chung et al. (2006).

part of the nasopharynx. During expiration, the maximum velocity was lower than that during inspiration. The main flow during expiration occurred in the middle airway, although expiratory air was reported to be approximately evenly distributed across the inferior, middle, and olfactory areas between the septum and the turbinate (Proctor, 1966; Swift and Proctor, 1977).

The flow patterns were similar in each inspiration and expiration period, and only differed in the magnitude of flow. These findings suggest similar flow patterns in the acceleration and deceleration phases of both inspiration and expiration (Fig. 4).

As reported by Tonndorf, eddies were noted when the inspiratory and expiratory phases change (Tonndorf, 1939; Chung et al., 2006). When expiration begins, multiple eddies can be identified in the anterior portion of the middle turbinate and nasopharynx. A small vortex was evident in the upper part of the soft palate in the middle portion of expiration. In the latter part of expiration, relatively large eddies occurred in the posterior part of the inferior turbinate and the upper part of the nasopharynx (Fig. 5).

4. Changes to nasal airflow in pathologic conditions

With cadaver models, changes in the nasal air currents were studied for pathologic conditions such as the presence of polyps, swelling, atrophy or resection of turbinates, and for enlarged adenoids (Tonndorf, 1939; Proetz, 1951; Swift and Proctor, 1977). The presence of polyps in the superior meatus, and generalized swelling of the turbinates seem to have the most effect on airflow pattern. As for the main pathway of airflow, the effects of various kinds of turbinectomy on nasal airflow are of great interest to rhinologists who must consider such aspects of surgical treatment prior to treating nasal obstruction.

4.1. Deviated nasal septum (DNS)

Although the prevalence of DNS is high as 22.38% in Korea (Min et al., 1995), the number of asymptomatic persons with DNS is higher than that of symptomatic patients. The presence of a septal spur alone has scarcely any effect on airflow patterns (Proetz, 1951). There are no published reports on the effect of septal deviation as evaluated using DPIV methods. We thus used DPIV to investigate patterns of nasal airflow in both nasal cavities of one asymptomatic DNS patient. Generally the patterns of airflow, stream lines and major pathways in the middle airway, were similar in both concave and convex sides with that of airflow in the normal nasal cavity. While the patency of both nasal cavities are influenced by many factors, including neurovascular control, and differs according to
Fig. 5. Streamline displays of nasal flow. Distribution of flow streams (A) during the beginning of inspiration, (B) in the middle of inspiratory acceleration, (C) at the maximal flow rate, and (D) in the middle of inspiratory deceleration. (E) Distribution during the change between inspiration and expiration. (F–I) Distributions during expiration with a large eddy at the posterior part of the inferior turbinate (each letter in the respiratory flow curve [center box] represents the location of each streamline). Modified from Chung et al. (2006).

The nasal cycle (Eccles, 2000), usually uniform widths of nasal airways were noted on each side in the CT or MR images in a manner more or less independent of the degree of septal deviation (Fig. 6). This phenomenon can be explained by the presence of compensatory hypertrophy of turbinates and developmental adaptation of other nasal structures (Grützenmacher et al., 2006). This may account for the nearly equal airflow patterns of nasal cavities with asymptomatic septal deviation.

Fig. 6. Reconstructed coronal CT images of the nasal cavity. In spite of the nasal septal deviation to the right side, the widths of the nasal airways are almost the same on both sides.
4.2. On the turbinectomy

4.2.1. Middle turbinectomy

The middle turbinate is located in the anterior portion of the middle nasal airway and its shape is thought to have an important influence on nasal airflow. Although there is no exact definition of the normal shape or size of the middle turbinate, it may be reshaped partially during endoscopic sinus surgery. Kim and Chung (2004a) used DPIV methods to measure changes to nasal airflow in three different models of turbinectomy: partial, anterior partial and total middle turbinectomy (Fig. 7) (Kim and Chung, 2004a). The airflow through the upper airway including the middle meatus was increased in the three turbinectomized models (Fig. 7B), as was the RMS velocity (Fig. 7C). These results are in rough agreement with the result that nasal airflow ventilated mainly in the middle airway after partial middle turbinectomy in a model of the decongested nasal cavity of a healthy test person (Grützenmacher et al., 2003). However, they are different from results showing that absence of the middle turbinate did not influence the overall flow pattern during inspiration and expiration with numerical and DPIV studies using schematic nasal cavity models (Hörschler et al., 2006).

The increase in RMS velocity after turbinectomy is consistent with the occurrence of eddies following atrophy of, or for a resected, middle turbinate in the nasal cavity models (Tonndorf, 1939).

4.2.2. Inferior turbinectomy

Because enlargement of the inferior turbinate is considered as a major cause of nasal obstruction, many turbinate procedures are done worldwide to enlarge the valve area and the inferior airway. We used the DPIV method to investigate the effect of three kinds of inferior turbinectomy – partial, anterior partial and total inferior turbinectomy – on nasal airflow. The three models of turbinectomy were created and compared with a normal model (Fig. 8). The main airflow through the middle airway, including the middle meatus, was not overly different between the two partial turbinectomy models. The main pathway of airflow in the totally resected model was altered in the middle and inferior airways and the lateral portion of the enlarged airway was filled with very low flow that was indicative of eddies. The RMS velocity was also increased in the two partially operated models (Fig. 8C).

In the total inferior turbinectomy model, the enlarged lower airway was not used as effective air tract. The inferior turbinate and...
spurs seemed to serve as guide vane to ensure a homogenous velocity distribution in the nasal cavity channels. In the case of total resection of the inferior turbinate, the flow field was characterized by massive vortices that impacted on flow distribution in the nasal cavity (Hörschler et al., 2006). Similar results were reported after total resection of the middle and inferior turbinate investigated with CFD methods (Lindemann et al., 2005).

In an airflow study using CFD methods, conservative, unilateral reduction of the inferior turbinate induced a broad reduction of pressure along the nasal airway (Wexler et al., 2005). Airflow changes were relatively regional: airflow in the valve area region was increased and the flow velocity was decreased. On the other hand, in a direct flow visualization study, virtually all of the flow was found to run through the lower nose section after an approximate 1-mm reduction of the medial and caudal side of the inferior turbinate (Grützenmacher et al., 2003). Our results of increased airflow through the middle airway after a partial inferior turbinectomy are different from the results of others. This difference may be due to different models and methods of surgical manipulation being used.

5. Future role of digital particle image velocimetry

The availability of well-made computer-generated models of the nasal cavity is the key to obtain reliable outcomes in the DPIV or CFD experiments. Thus, for the basis of a model, it is recommended to use the data of axial image taken from not decongested nasal cavities reconstructed to less than 1.25 mm in slices thickness. Until now, 2D vector of sagittal plane, which is major component of nasal airflow, has been investigated with DPIV techniques.

Although the secondary flow from major axial flow is small in the nasal cavity, secondary flow is anticipated along the anterior surface of the middle turbinate during quiet inspiration and in the posterior space of the inferior turbinate during expiration. Also, laterally located eddies are anticipated after structural modifications. This phenomenon cannot be resolved accurately with the 2D DPIV method. To obtain a more detailed 3D airflow pattern, evaluation of the 3 components of nasal airflow velocity should be investigated with the 3D DPIV technique.

Evaluation of normal patterns of nasal airflow in certain populations is very difficult because constructing many DPIV models and performing detailed measurements requires a great deal of time.

Fig. 8. Changes to nasal airflow after 3 kinds of inferior turbinectomies. Schematic drawing of inferior turbinectomies (A). Colored areas depict the location and amount of resection. c: control model, 1: anterior inferior partial, 2: anterior partial, 3: total inferior turbinectomy. In (B), average velocity is displayed in coronal planes. Main airflows were noted in the middle airway in the control model and the anterior partial turbinectomy model. For the total turbinectomy model, the main stream was found between the middle and inferior airway in the mid portion and in the inferior airway in the posterior portion of the nasal cavity. In (C), RMS velocity is reconstructed in coronal planes. Values of RMS velocity were increased in partial turbinectomy models and decreased in the total turbinectomy model.
This problem can be solved with CFD methods, for which DPIV serves as an essential method to verify results. As such, the two methods complement each other.

The DPIV technique can also be extended to include the pharynx, larynx, trachea and bronchus (Fresconi and Prasad, 2007; Kim and Lee, 2007; van Erbruggen et al., 2008).

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References


