Visualization of Flow Resistance in Physiological Nasal Respiration

Analysis of Velocity and Vorticities Using Numerical Simulation

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Objectives: To visualize the velocity gradients and the vorticities of physiological unsteady nasal flow using the computational fluid dynamics method and to compare the inspiratory phase and expiratory phase flow patterns.

Design: An anatomically correct 3-dimensional nasal and pharyngeal cavity was constructed from computed tomographic images of a healthy adult nose and pharynx. The unsteady state Navier-Stokes and continuity equations were solved numerically on inspiratory and expiratory nasal flow.

Setting: Numerical simulation application.

Participants: Coronary and axial computed tomographic images from a healthy adult were used.

Main Outcome Measures: The detailed velocity distribution and vorticity (resistance) distribution of nasal airflow were visualized using the computational fluid dynamics method (an imaging technology for regional flow factors [velocity, vector, streamline, and vortex]).

Results: In the inspiratory phase, a high-velocity area was prominent in the middle meatus, and the highest vorticity area had good agreement with this region. In the expiratory phase, the distributions of velocity and vorticities were flatter than those in the inspiratory phase.

Conclusion: The computational fluid dynamics model allows the investigation of airflow elements under physiological conditions, as well as the examination of the effect of nasal structure.

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One of the basic respiratory functions of the nose is to maintain an airway resistance appropriate for physiological needs. To investigate this function, many researchers have studied the airflow profiles in nasal respiration.1-7 These studies provide valuable descriptions of nasal airflow patterns; however, quantitative information on the nasal airflow is limited. Rhinomanometry and acoustic rhinomanometry have been used clinically to evaluate nasal resistance. Rhinomanometry and acoustic rhinomanometry have been used clinically to evaluate nasal resistance. Rhinomanometry is used to measure the pressure required to produce airflow through the nasal airway,8 and acoustic rhinomanometry is used to measure the cross-sectional area of the airway at various nasal planes.9 The combined use of these methods is advantageous in the evaluation of the nasal airway.10 However, measuring the precise velocity of airflow and evaluating the local nasal resistance in every portion of the nasal cavity have proven to be difficult.

Computational fluid dynamics (CFD) is a numerical simulation application that enables the visualization of flow factors (velocity, pressure, vector, streamline, and vorticity or [amount of vortex]) under various flow conditions. Many researchers have conducted CFD studies11-20 of the human nasal airway; however, most of these investigations did not focus on the factor of vorticity. In addition, their analyses were performed under almost a steady flow condition, which differs from that of physiological nasal respiration (an unsteady flow condition).

Air is classified as a Newtonian fluid (a flow with viscosity), which is different from an ideal fluid (a flow without viscosity) and a perfect fluid (a flow without viscosity and compressibility). In addition, air can be considered approximately incompressible if the flow velocities are low compared with the speed of sound (340 m/s in air). Viscosity is an internal property of a fluid that offers resistance to flow. In the case of an inner flow such as the nasal flow, the molecules next to the wall surface have zero velocity if the fluid is viscous. In a viscous flow, a velocity gradient is generated, and the adjacent flows with

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different velocities produce a vortex (Figure 1). The shape of the mass rotating rapidly around a center forms a vortex (a spiral motion with closed streamlines). Vorticity is a mathematical concept used in fluid dynamics to describe the amount of rotation in a fluid. Vorticity is thought of as an energy loss (resistance) of the flow from upstream to downstream. By visualizing all vortices generated during nasal respiration, the distribution of resistance during nasal respiration can be determined.

The objectives of this study were (1) to visualize the velocity gradients and the vorticities of unsteady nasal flow (which cannot be measured by rhinomanometry and acoustic rhinomanometry) using the CFD method and (2) to compare the difference in the flow patterns between the inspiratory and expiratory nasal flows. To our knowledge, this investigation is the first attempt to include the vorticity profile and nasal geometry in a theoretical model of the nasal flow pattern.

The complex structure of the nose has a physiological function. However, it is difficult to estimate the nasal flow pattern outside of the surgical setting. The CFD method can be effectively used to estimate the physiological function of the nose.

**ANATOMICAL DATA**

To construct an anatomically correct 3-dimensional model of the nasal and pharyngeal cavities, 141 sections from a computed tomographic image of a single subject were used. The images were obtained at intervals of 1 mm from the anterior tip of the nose to the posterior end of the pharynx. The 3-dimensional geometry of the nasal and pharyngeal cavities was reconstructed from the DICOM (digital imaging and communications in medicine) data of the computed tomographic im-
age sections using the imaging software INTAGE 3.1 (KGT Co, Tokyo, Japan). After necessary smoothing and artifact correction, a 3-dimensional mesh was created that was denser near the walls and coarser in regions where small velocity gradients existed; mesh-generating software called Gambit (Fluent Inc, Lebanon, NH) was used for this purpose. The final mesh representing the nasal cavity contained 1,207,673 elements (Figure 2).

NUMERICAL SIMULATION OF AIRFLOW

The air was assumed to be a Newtonian, homogeneous, and incompressible fluid. Navier-Stokes equations and the continuity equation were used in the study. Navier-Stokes equations are a set of equations that describe the motion of fluid substances. The equations establish that the changes in the momentum of the particles of a fluid are simply the product of the changes in the pressure and dissipative viscous forces acting inside the fluid. The continuity equation is an equation of conservation of mass. The computation code used was the Fluent 6.1.22 simulation package (Fluent Inc). The computations were performed using a personal computer with a Pentium 4 central processing unit and 2 gigabytes of memory, which typically took 28 days per run to complete. The simulated airflow was in an unsteady state in the inspiratory and expiratory directions. We assumed the tidal volume to be 500 mL and the breath frequency to be 12 per minute (ie, inspiratory phase, 2.5 seconds; resting phase, 0.1 second; expiratory phase, 2.5 seconds; and resting phase, 0.1 second). The time variance in the velocity of airflow was defined by the sine wave function (Figure 3). The following boundary conditions were set: The nasal cavity wall was set as a no-slip condition. The velocity of airflow was given at the nares. A pressure value of zero was assumed at the mesopharynx. The flow velocity distribution at the nares was set at a uniform flow. One cycle was simulated initially before the final (second) run was completed to obtain an accurate solution description. The convergence of solution was measured within 0.001 relative to continuity and velocity.

RESULTS

The simulated flow has maximum velocity and vorticity at 1.25 seconds during the inspiratory phase (Figure 3A) and at 3.85 seconds during the expiratory phase (Figure 3B); these correspond to the Reynolds number (ratio of inertial to viscous forces) of 1200 at the nostril. The locations of the coronal planes at the nasal vestibule (plane A), nasal valve (plane B), anterior portion of the inferior turbinate (plane C), anterior portion of the middle turbinate (plane D), mid portion of the middle turbinate (plane E), and posterior portion of the inferior turbinate (plane F) are shown in Figure 4. The flow simulation results on these planes are presented.

The velocity contour plots obtained from the numerical computations at the mid inspiratory phase are shown in Figure 5; the maximum velocity at each plane differs. The highest velocity in the nasal cavity was recorded along the middle meatus. In plane A, the peak velocity was observed close to the anterolateral portions. As the flow moves toward plane B, the peak velocity remained within the middle portion on the right side and within the upper third portion on the left side; the peak

**Figure 5.** The maximum velocity contour at 1.25 seconds (the point of Figure 3A) during inspiration. The results are presented in the coronal planes (A-F) as listed in Figure 4. Maximum velocities are 3.50 m/s on plane A, 3.40 m/s on plane B, 3.15 m/s on plane C, 2.30 m/s on plane D, 2.10 m/s on plane E, and 1.80 m/s on plane F.
velocity on the left side is lower than that on the right side. In plane C, the peak velocities of both nasal sides decrease, with the same velocity distribution as in plane B. In planes D through F, the peak velocity was observed along the middle meatus and close to the middle turbinates. The lowest velocity in the nasal cavity was recorded in the superior regions of the nasal cavity (planes B through E) and in the upper lateral portions of the inferior turbinates (planes C through E). The peak airspeed in each plane decreases posteriorly. The difference in velocity distributions between the right and left nasal cavities during the inspiration phase was significant in the anterior planes (planes B and C).

The vortex contour plots in the coronal planes that were obtained from the numerical computations during the mid inspiratory phase are shown in Figure 6. High vorticities were recorded at the anterior portion of the nasal cavity (planes A through C) and at the area close to the middle turbinate at the posterior portion of the nasal cavity. The regions with high vorticities were the same as the regions with a sharp velocity gradient in Figure 5.

The velocity contour plots obtained from the numerical computations during the mid expiratory phase are shown in Figure 7. The results are arranged in the order of flow direction in the coronal planes (planes F through A) indicated in Figure 4. The highest velocity in the nasal cavity was recorded along the common nasal meatus. In planes E and C, a relative wide peak is in the common nasal meatus. In planes B and A, the velocity distribution was uniform. The lowest velocity in the nasal cavity was recorded in the superior regions of the nasal cavity (plane D) and in the upper lateral portions of the inferior turbinates (planes E and D). The peak airspeed at each plane increases anteriorly. As observed during the inspiratory phase, there was no difference in the velocity distributions between the right and left nasal cavities during the expiratory phase.

The vortex contour plots in the coronal planes obtained from the numerical computations during the mid expiratory phase are shown in Figure 8. High vorticities were recorded at the anterior portion of the nasal cavity (planes A through C) and at the area along the common nasal meatus at the posterior portion of the nasal cavity. The regions with high vorticities were similar to the regions with a sharp velocity gradient in Figure 7.

**COMMENT**

Experiments on nasal flow using noselike models are problematic because the measuring equipment may disturb the flow. To circumvent these difficulties, the CFD method has been used for analyzing the nasal flow. However, CFD studies on human nasal flow have focused on velocity, streamline, and heat transfer analysis but not on resistance analysis. Moreover, most studies evaluated the nonphysiological steady flow condition.

The primary objectives of this study were (1) visualize the velocity gradients and the vorticities of physiological unsteady nasal flow using the CFD method and
(2) to compare the flow patterns during the inspiratory and expiratory phases. To our knowledge, our study is the first trial to establish a computational model simulating the intranasal vorticity profiles during physiological nasal respiration. To obtain accurate results, various computational conditions were used in this model, the most notable of which is a physiological breathing cycle (the time variance in the velocity of airflow was defined by the sine wave function). The steady flow assumption used in previous studies\textsuperscript{13,14,18-20} has been confirmed at normal breathing rates; the unsteady effect of vortex on the flow was ignored in the model because no experimental data on vorticity during nasal respiration were collected. In addition, the anatomical reconstruction of computed tomographic images used sections that were 1 mm apart; this provides a more detailed resolution of the structure of the nose than that provided by the models by Keyhani et al\textsuperscript{13} (2 mm apart) and by Subramaniam et al\textsuperscript{14} (1.5 mm apart). In addition, a denser mesh containing more than 1.2 million elements was created for the nasal and pharyngeal model in our study; this was considered adequate with regard to accuracy.

The velocity profiles in the inspiratory and expiratory phases (Figures 4 and 6) are generally consistent with those obtained in the study by Hahn et al\textsuperscript{8} and in the numerical simulation by Keyhani et al.\textsuperscript{13} Using numerical simulation, Elad\textsuperscript{11} and Keyhani\textsuperscript{13} and their colleagues determined that the primary route of airflow through the nose tends to follow along the nasal floor. In contrast, Hornung\textsuperscript{2} and Schreck\textsuperscript{22} and their colleagues found that it tends to follow along the middle meatus. Arbour et al\textsuperscript{12} and Subramaniam et al\textsuperscript{14} used laser anemometry and numerical simulation, respectively, and observed that the airflow tends to follow along the middle and inferior meatus. Our results show that the area with peak flow velocity in the inspiratory phase was located along the middle and inferior meatus on the right side and along the middle meatus on the left side, a difference due to the shape of the anterior nasal portion. The computed tomographic images of the anterior nasal segment revealed that the medial space of the right inferior turbinate was slightly narrower than that of the left nasal cavity due to the enlargement of the right inferior turbinate. We believe that this difference produces the dominant flow in the middle meatus. In contrast, the area with peak flow velocity in the expiratory phase is flatter and wider than that in the inspiratory phase, as observed in the studies by Proetz\textsuperscript{1} and Keyhani et al.\textsuperscript{13}

The vortex profiles in the inspiratory and expiratory phases (Figures 6 and 8) show the 3-dimensional distribution of vorticities in the mid inspiratory and mid expiratory phases. The regions with high vorticities were similar to the regions with a sharp velocity gradient, and these areas were located at the anterior portion of the nasal cavity (planes A through C), as reported by Cole.\textsuperscript{23} Our results are consistent with the fact that the narrowest segment in the nasal passage is the main site of nasal resistance. In the narrow segment, the air velocity is increased, and the velocity gradient is sharpened. The adjacent flows with sharp velocity gradients produce a greater vortex (seed of resistance). There are no other
The existence of a vortex does not imply that the flow is turbulent. Turbulent flow is a flow with an unstable vortex. In recent years, it has become clear that the physics of turbulent flows is significantly affected by the dynamics of organized vortical structures. Turbulent flow is unsteady and 3-dimensional, it possesses considerable vorticity, and a plot of the velocity as a function of time seems to be random. Because our study was performed under the conditions of respiration at rest, the plot of vorticities as a function of time was not random; therefore, the flow was assumed to be laminar.

The 3-dimensional distribution of a vortex is considerably different in the inspiratory and expiratory phases. In the inspiratory phase, the sites of airflow resistance are localized along the anterior portion of the middle meatus. In the expiratory phase, they are localized near the nasal wall (Figure 9). This finding explains the functions of inspiratory and expiratory nasal breathing. Because the area with high vorticities is located along the middle meatus during the inspiratory phase, the contact between the inspiratory air and the surrounding mucosa will be more intensive and will provide effective cleansing, warming, and humidification during inspiratory nasal respiration.

There are limitations to our study. First, experimental verification of our results was not carried out. However, flow experiments in complex structures such as the nose are difficult; therefore, it is essential to devise new experimental methods. Second, our study is a single-model study; therefore, the results cannot be applied to different noses. More simulations using other models with different shapes are needed.

Figure 8. The maximum vorticity contours at 3.85 seconds (the point of Figure 3B) during expiration. The results are presented in the coronal planes (A-F) as listed in Figure 4.

Figure 9. Comparison of the velocity and vortex of the nasal flow between the mid inspiratory phase and the mid expiratory phase at the anterior (plane C) and posterior (plane E) portions of the right nasal cavity. Exp indicates expiratory; Ins, inspiratory.
Numerical simulation allows a 3-dimensional display of intranasal velocity and vorticity distributions that cannot be obtained using in vivo measurements. The close relationship between intranasal air velocity and air vorticity is demonstrated by numerical simulation. The method used herein could provide additional information for planning nasal surgical procedures.

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