Flow Mechanisms in the Human Olfactory Groove

Numerical Simulation of Nasal Physiological Respiration During Inspiration, Expiration, and Sniffing

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Objectives: To visualize the velocity and the streamline of physiological unsteady nasal flow and sniffing using the computational fluid dynamics method and to compare the inspiratory phase, expiratory phase, and sniffing flow patterns of the olfactory area.

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 and sniffing.

Setting: Numerical simulation application.

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

Results: The inspiratory flow passes through a wider olfactory area than the expiratory flow, and the sniffing flow passes through the widest olfactory area without increasing the velocity of the airflow. In addition, a recirculating flow strongly promotes olfactory function.

Conclusion: The computational fluid dynamics model allows for the investigation of the flow mechanisms in the human olfactory groove.


Human olfaction is a process that involves the transfer of odorant molecules to the olfactory epithelium located in the upper part of the human nasal cavity (olfactory groove). Although molecules can reach the olfactory epithelium by diffusion, olfaction essentially requires some type of nasal airflow, usually as a part of inhalation. While significant advances have been made in understanding functional odor perception, the manner in which odorant molecules reach the human olfactory epithelium is not completely understood. Sniffing is an almost universally performed maneuver when a person is presented with an olfactory stimulus. It is possible that its purpose is to momentarily increase the number of olfactory molecules reaching the olfactory groove by causing a transient change in the airflow pattern in the nose. However, the effect of sniffing on the in vivo airflow pattern remains unknown. The basic questions that have not been adequately addressed are regarding our ability to smell an odor during the inspiratory phase but not during the expiratory phase and the need to sniff an odor for better odor perception.

Airflow profiles in human nasal cavities have been investigated by a number of researchers using in vitro models. The earliest nasal physical models were usually cast from the noses of human cadavers. Quantitative measurement in these casts was performed by visualizing smoke airflow and by using miniature Pitot tubes, laser Doppler velocimetry, and radioactive tracers. To increase the spatial resolution and accuracy of measurement, enlarged models of the nasal cavity have also been constructed based on magnetic resonance images and computed tomographic (CT) images. Hahn et al constructed an anatomically accurate, enlarged-scale (×20) physical model of the right human nasal cavity from coronal CT images. Although these studies provided valuable descriptive and quantitative information on airflow patterns in the na-
With the development of a technique based on computational fluid dynamics (CFD), the characteristics of human nasal flow, including those of human olfactory flow, could be predicted using mathematical models of the nose created from CT images. These theoretical results obtained under steady-flow conditions are in agreement with human experimental data.

It is generally agreed that the human olfactory epithelium is located high in the nasal cavity, predominantly on the dorsal aspects of the nasal vault, septum, and superior turbinate (Figure 1A). However, based on histological and electro-olfactogram studies, Leopold et al reported in 2000 that the human olfactory epithelium was probably more anterior in location than previously assumed. Moreover, Ishimaru made the same observation based on an optical recording of the intrinsic signal from the human olfactory groove.

The principal goals of the CFD analyses are to shed light on how the human nose functions, to test the current model with regard to olfactory function, and to search for signatures that may clarify the nature of the human nose. These goals can be achieved by accurate simulation of human physiological respiration. We describe herein a nasal respiratory simulation of physiological (unsteady) flow conditions and of sniffing, which was performed by using an anatomically correct 3-dimensional (3-D) nasal and nasopharyngeal cavity model constructed from human CT images. Based on new evidence from a recent study of the distribution of the human olfactory epithelium, we followed the location and

Figure 1. Anatomical location of the olfactory area, the 3-dimensional finite element mesh of the nasal and pharyngeal cavities, and the time variance in the airflow velocities using the flow simulation. A, Coronal computed tomographic (CT) images of the human nasal cavity. The medial wall of the nasal cavity is formed by the septum and the lateral wall and by mucosal swellings called the inferior, middle, and superior turbinates. These lateral components impart complicated contours to the nasal cavity. The olfactory area is located in the upper part of the nasal epithelium (arrow). The left and right portions of the figure depict the anterior and middle coronal slices, respectively. B, Lateral view of the nasal cavity. The olfactory epithelium has been thought to be located below the olfactory bulb (area i). However, based on histological and electro-olfactogram studies, Leopold et al reported in 2000 that the human olfactory epithelium was probably more anterior in location than previously assumed (area ii). C, A 3-dimensional finite element mesh of the nasal and pharyngeal cavities. The model partially lacks the uppermost portion because it is closely based on the original CT images. The nasal cavity mesh contains 1,207,673 elements. D, Time variance in the airflow velocities, defined by the sine wave function. We assumed that during respiration, the tidal volume was 500 mL and breathing frequency, 12/min (inspiratory phase, 2.5 seconds; resting phase, 0.1 second; expiratory phase, 2.5 seconds; and resting phase, 0.1 second). The tidal volume during sniffing was assumed to be 200 mL (sniffing phase, 0.5 second, and resting phase, 0.1 second).
Anatomical data have been presented in our previous study. To construct an anatomically correct 3-D model of the nasal and pharyngeal cavities, 141 sections from a CT image of a single subject were used after obtaining informed consent. 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-D geometry of the nasal and pharyngeal cavities was reconstructed based on the DICOM (digital imaging and communications in medicine) data of the CT scan sections by using the imaging software Intage 3.1 (KGT Co, Tokyo, Japan). After necessary smoothing and artifact correction, we created a 3-D mesh that was denser near the walls and coarser in regions where the velocity gradients are small; a mesh-generating software (Gambit; Fluent Inc, Lebanon, New Hampshire) was used for this purpose. The final mesh representing the nasal cavity contained 1,207,673 elements (Figure 1C).

In this study, we used the same model as that used previously, with modeling assumptions and parameters adjusted to fit the observed properties of physiological human nasal respiration and sniffing. 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. These equations establish that the changes in the momentum of the particles of a fluid are merely a product of the changes in the pressure and dissipative viscous forces acting inside the fluid. The continuity equation is an equation for the conservation of mass. The Fluent 6.1.22 simulation package (Fluent Inc) computation code was used. The simulated airflow was maintained in an unsteady state during both the inspiratory and expiratory phases and during sniffing. We assumed the tidal volume to be 300 mL and the breathing frequency to be 12/min (inspiratory phase, 2.5 seconds; resting phase, 0.1 second; expiratory phase, 2.5 seconds; and resting phase, 0.1 second) during nasal respiration. During sniffing, we assumed the tidal volume to be 200 mL (sniffing phase, 0.5 second, and resting phase, 0.1 second). The time variance in the airflow velocity in the nostril was defined by the sine wave function (respiratory phase, 0.1 second). The time variance in the airflow velocity to be 200 mL (sniffing phase, 0.5 second, and resting phase, 0.1 second). The time variance in the airflow velocity in the nostril was 3.2 m/s, that in the UMSL was 0.2 m/s. The shape and location of the RCF did not change during the inspiratory phase (Figure 3A, cycles 5/16-15/16). During the right inspiratory phase (Figure 3B), as the velocity increased, the UMSL moved up to the olfactory area (Figure 3A, cycles 5/16-15/16). The location of the UMSL during the midinspiratory phase (Figure 3A, cycle 4/16) was higher than that during the midexpiratory phase (Figure 3A, cycle 12/16). During the right expiratory phase (Figure 3B), as the velocity increased, the UMSL moved down from the olfactory area (Figure 3B, cycles 13/16-15/16) and reached the highest level at a point in the 4/16th cycle of respiration (videos 4 and 5 are available at http://archoto.com). When the airflow velocity in the nostril was 2.5 m/s, that in the UMSL was 0.3 m/s. The location of the UMSL during sniffing was higher than that during inspiration (Figure 3A). During the right inspiratory phase (Figure 3A), as the velocity increased, a recirculating flow (RCF) was generated in the olfactory area (Figure 3A, cycles 1/16-3/16) and reached the highest level at a point in the 4/16th cycle of respiration (videos 4 and 5 are available at http://archoto.com). When the airflow velocity in the nostril was 2.5 m/s, that in the UMSL was 0.3 m/s. The UMSL did not move up as the velocity decreased (Figure 2A, cycles 5/16-7/16). During the right expiratory phase (Figure 2B), as the velocity increased, the UMSL moved down from the olfactory area (Figure 2B, cycles 9/16-11/16) and reached the lowest level at a point in the 12/16th cycle of respiration (videos 1 and 2 are available at http://archoto.com). When the airflow velocity in the nostril was 2.5 m/s, that in the UMSL was 0.4 m/s. The UMSL did not move up as the velocity decreased (Figure 2B, cycles 13/16-15/16). The location of the UMSL during the midinspiratory phase (Figure 2A, cycle 4/16) was higher than that during the midexpiratory phase (Figure 2A, cycle 12/16). During the left sniffing phase (Figure 2C), as the airflow velocity increased, the UMSL moved up to the olfactory area (video 3 is available at http://archoto.com). When the airflow velocity in the nostril was 8.0 m/s, that in the UMSL was 0.3 m/s. The location of the UMSL during sniffing was higher than that during inspiration (Figure 3A and C).

We show the results of the simulation as a streamline profile with airflow velocity at every 1/16th cycle of nasal respiration and after 0.1, 0.2, 0.4, and 0.5 second of sniffing. During the left inspiratory phase (Figure 2A), as the velocity increased, the UMSL moved up toward the olfactory area (Figure 2A, cycles 1/16-3/16) and reached the highest level at a point in the 4/16th cycle of respiration (videos 1 and 2 are available at http://archoto.com). When the airflow velocity in the nostril was 3.2 m/s, that in the UMSL was 3.2 m/s. The UMSL did not move down as the velocity decreased (Figure 2A, cycles 5/16-7/16). During the right expiratory phase (Figure 2B), as the velocity increased, the UMSL moved down from the olfactory area (Figure 2B, cycles 9/16-11/16) and reached the lowest level at a point in the 12/16th cycle of respiration (videos 1 and 2 are available at http://archoto.com). When the airflow velocity in the nostril was 2.5 m/s, that in the UMSL was 0.4 m/s. The UMSL did not move up as the velocity decreased (Figure 2B, cycles 13/16-15/16). The location of the UMSL during the midinspiratory phase (Figure 2A, cycle 4/16) was higher than that during the midexpiratory phase (Figure 2A, cycle 12/16). During the left sniffing phase (Figure 2C), as the airflow velocity increased, the UMSL moved up to the olfactory area (video 3 is available at http://archoto.com). When the airflow velocity in the nostril was 8.0 m/s, that in the UMSL was 0.3 m/s. The location of the UMSL during sniffing was higher than that during inspiration (Figure 3A). During the right inspiratory phase (Figure 3A), as the velocity increased, a recirculating flow (RCF) was generated in the olfactory area (Figure 3A, cycles 1/16-3/16) and reached the highest level at a point in the 4/16th cycle of respiration (videos 4 and 5 are available at http://archoto.com). When the airflow velocity in the nostril was 2.5 m/s, that in the UMSL was 0.3 m/s. The UMSL did not move up as the velocity decreased (Figure 3B, cycles 13/16-15/16). The location of the UMSL during the midinspiratory phase (Figure 3A, cycle 4/16) was higher than that during the midexpiratory phase (Figure 3A, cycle 12/16). During the right sniffing phase (Figure 3C), as the velocity increased, RCF was generated in the olfactory area, and the UMSL moved up to the olfactory area (video 6 is available at http://archoto.com). When the airflow velocity in the nostril was 8.5 m/s, that in the UMSL was 0.3 m/s. The location of the UMSL during sniffing was higher than that during inspiration (Figure 3A, A and C), and the streamlines of the RCF observed during sniffing were denser than those observed during inspiration (Figure 3A, A and C). Figure 4 shows the comparison of the streamlines of the nasal flow during the midinspiratory and midexpiratory phases and at the end of the sniffing phase in both nasal cavities in the anterolateral view.

Figure 5 shows the streamline profiles during the first half of the inspiratory phase and during sniffing and the airflow velocity in the nostril. This figure indicates the relationship between the height of the UMSL and the airflow velocity in the nostril; when the latter increases, the UMSL moves up in continuity.

Experiments performed on narrow-slit flows such as those in the human olfactory groove by using noselike models

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have drawbacks because of the limited accuracy of measuring equipment. To circumvent these difficulties, the CFD method has been used for analyzing human olfactory flows.7,17,18

The primary objectives of this study were (1) to visualize the velocity and streamlines during physiological unsteady nasal flow and sniffing by using the CFD method and (2) to compare the flow patterns in the olfactory area during the inspiratory, expiratory, and sniffing phases. To obtain accurate results, various computational conditions were used in this model. We assumed the tidal volume to be 500 mL, and the time variance in the airflow velocity was defined by the sine wave function for simulating physiological nasal respiration. During sniffing, we assumed the tidal volume to be 200 mL, and the time variance in the airflow velocity in the nostril was defined by the quarter of the sine wave function. Anatomical reconstruction of the CT images was performed using sections that were 1 mm apart, and a denser mesh containing more than 1.2 million elements was created for the nasal and pharyngeal model in our study; this was considered to be adequately accurate.

Although there are no precise experimental data on olfactory flows, the velocity and streamline profiles in

Figure 2. Representative time-lapse images of the streamlines in the left nasal flow. Time-lapse images were obtained at every 1/16th cycle during nasal respiration and after 0.1, 0.2, 0.4, and 0.5 second of sniffing. The area of the left nasal cavity is shown in light gray. A, Streamline profiles during left nasal inspiration (cycles 1/16-7/16). B, Streamline profiles during left nasal expiration (cycles 9/16-15/16). C, Streamline profiles during left nasal sniffing (0.1-0.5 second). D, Olfactory areas that were assumed in previous (i) and recent (ii) periods.
the olfactory region during inspiration in this study are largely consistent with those obtained by Zhao et al\textsuperscript{10} and Croce et al\textsuperscript{18} in their numerical simulations. Croce et al\textsuperscript{18} reported a velocity of 0.4 m/s in the olfactory groove during the midinspiratory phase when that in the nostril was 3.1 m/s. We calculated the velocity to be 0.3 m/s (left) and 0.2 m/s (right) in the olfactory groove during the midinspiratory phase when that in the nostril was 3.2 m/s.

The most interesting finding, which was obtained only under unsteady-flow simulations, was the displacement of the UMSL during respiration. As the velocity increased, the UMSL moved closer to the olfactory area, and it moved away from the olfactory area as the velocity decreased. This may explain why we smell an odor during the inspiratory phase but not during the expiratory phase. The difference in the flow patterns during the inspiratory and expiratory phases was attributed to the structural difference between the anterior and posterior nasal components. As previously shown (Figure 1A), the anterior nasal cavity is narrow, and the turbinate head directs the flow in different directions. In contrast, the posterior end is wide and circular. Hence, the expiratory airflow is directed along the turbinate.

![Figure 3. Representative time-lapse images of the streamlines in the right nasal flow.](image)
Another interesting finding was the existence of the RCF in the olfactory groove. In our study, an RCF was generated unilaterally (right side). Zhao et al.\(^{10}\) reported a similar unilateral RCF, whereas Croce et al.\(^{18}\) reported bilateral RCFs in the olfactory groove on steady-state CFD analysis of the nose.\(^{18}\) Croce et al.\(^{18}\) described that airflows can be divided into 2 parts. The first part of the airflow, which has relatively high velocity, passes through the lower half of the nasal cavities and therefore appears to be primarily concerned with respiration. The second part of the airflow, which has a much lower velocity, passes through the upper half of the nasal cavities and is probably concerned with olfaction. We agree with their conclusion. In our study, the location of the UMSL in the RCF-positive flow (right) was higher than that in the RCF-negative flow (left) during the inspiratory phase and sniffing. We considered the existence of the RCF to be advantageous for olfactory flow. In addition, we thought that these advantages are the distribution and circulation of air over a wide olfactory area, thereby amplifying olfactory stimuli.

As shown in Figure 3A, the fast, narrow flow along the middle...
meatus (the space between the middle and inferior turbinates) generates a detached RCF in the anterior part of the nasal cavity. Several factors have been proposed regarding the lateralization of olfactory sensitivity, including anatomical difference of nostril, handedness and nasal side sensitivity, intranasal volume, and laterality of the processing in central nervous system. We thought that the existence of RCF might affect the laterality of olfactory sensitivity.

Our study visualized the streamlines during sniffing. Figure 4A confirms that sniffing is merely an extension of inspiration. Although there are many functional magnetic resonance imaging studies indicating the role of the central nervous system in sniffing, our results clarify that human sniffing is a mechanism involving airflows. On both sides, the position of the UMSL during sniffing was higher than that during inspiration. Although the velocity in the nostril during the sniffing phase was higher than that during the inspiratory phase, the velocity of the UMSL during sniffing was almost the same as that during the inspiratory phase; only the height of the UMSL differed. Zhao et al. reported in a numerical study that the transport of odorants onto the olfactory mucosa during sniffing was remarkably similar to that during resting breathing. The purpose of sniffing is thought to be to increase the number of olfactory molecules that reach the olfactory groove by causing a transient change in the airflow pattern in the nose. However, based on our findings, we hypothesize that sniffing behavior enables the odorant flow to cover a wider olfactory area than that during usual inspiration.

There are certain limitations to our study. First, experimental verification of our results was not carried out. However, flow experiments in complex and narrow structures such as the olfactory groove are difficult; therefore, it is essential to devise new experimental methods. Second, our study is a single-model study performed under a single flow condition; therefore, the results cannot be generalized. More simulations using other models with different shapes and calculation conditions are required. Third, our study did not consider the diffusion effects of odorants. However, we believe that diffusion effects will not affect our conclusion because the velocities of most odorants are very low (<0.001 m/s) compared with the velocity of the UMSL in our simulation (0.3 m/s).

By introducing entirely unsteady calculations into the nasal CFD study, we can obtain many important findings regarding flow mechanisms in the human olfactory groove under several respiratory conditions. The CFD study is an important tool for understanding the functions of the human nose.

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Author Contributions: Dr Ishikawa had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Ishikawa and Matsuzawa. Acquisition of data: Watanabe. Analysis and interpretation of data: Nakayama. Drafting of the manuscript: Ishikawa.

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