Published in final edited form as:

Biomech Model Mechanobiol. 2020 October ; 19(5): 1447–1459. doi:10.1007/s10237-019-01280-9.

Effects of velopharyngeal openings on flow characteristics of nasal emission

Elias Sundström^{1,*}, Suzanne Boyce², Liran Oren¹

¹Department of Otolaryngology-Head and Neck Surgery, University of Cincinnati, 231 Albert Sabin Way, Cincinnati, Ohio 45267, USA.

²Department of Communication Sciences & Disorders, University of Cincinnati, 3202 Eden Avenue, Cincinnati, Ohio 45267, USA.

Abstract

Nasal emission is a speech disorder where undesired airflow enters the nasal cavity during speech due to inadequate closure of the velopharyngeal valve. Nasal emission is typically inaudible with large velopharyngeal openings and very distorting with small openings. This study aims to understand how flow characteristics in the nasal cavity change as a function of velopharyngeal opening using computational fluid dynamics. The model is based on a subject who was diagnosed with distorting nasal emission and a small velopharyngeal opening. The baseline geometry was delineated from CT scans that were taken while the subject was sustaining a sibilant sound. Modifications to the model were done by systematically widening or narrowing the velopharyngeal opening while keeping the geometry constant elsewhere. Results show that if the flow resistance across the velopharyngeal valve is smaller than resistance across the oral constriction, flow characteristics such as velocity and turbulence are inversely proportional to the size of the opening. If flow resistance is higher across the velopharyngeal valve than the oral constriction, turbulence in the nasal cavity will be reduced at a higher rate. These findings can be used to generalize that the area ratio of the velopharyngeal opening to the oral constriction is a factor that determines airflow characteristics and subsequently its sound during production of sibilant sound. It implies that the highest level of turbulence in the nasal cavity, and subsequently the sound that will likely be perceived as the most severe nasal emission, is produced when the size of openings is equal.

Keywords

Nasal emission; velopharyngeal valve opening; turbulence; computational fluid dynamics

Terms of use and reuse: academic research for non-commercial purposes, see here for full terms. <https://www.springer.com/aam-terms-v1>

*Corresponding author, sundstes@uc.edu, +1 (513) 558-1181.

Conflict of interest

The authors declare that they have no conflict of interest that could influence their work.

Publisher's Disclaimer: This Author Accepted Manuscript is a PDF file of an unedited peer-reviewed manuscript that has been accepted for publication but has not been copyedited or corrected. The official version of record that is published in the journal is kept up to date and so may therefore differ from this version.

1 Introduction

The velopharyngeal (VP) valve regulates the coupling between the oral and nasal cavities during speech. The VP valve can be fully open for nasal sounds (e.g., /m/, /n/, and /ŋ/), partially open (e.g., nasalized vowels), and fully closed (e.g., high-pressure sounds such as /s/ or word-initial /p/). The opening/closing of the VP valve determines how airflow and sound are channeled from the pharynx into the nasal and oral cavities.

Inadequate closure of the VP valve during speech will generate a speech disorder because of undesired airflow and/or resonance in the nasal cavity. The underlying mechanism for incomplete closure can be obligatory (due to abnormal structure, known as velopharyngeal insufficiency [VPI]) or compensatory (due to articulation errors). The perceived size of the VP opening has been shown to be a good predictor of speech disorder type, but not severity (Kummer et al. 2003).

A large opening of the VP valve is typically associated with hypernasality. In hypernasality, high-pressure sounds are often substituted or compensated because of the speaker's inability to build up the necessary (oral) pressure. A large VP opening allows for undesired sound from the vocal tract to resonate in the nasal cavity, which is perceived mostly during vowels and voiced consonants.

Nasal emission is typically inaudible with large VP openings. In this case, any sound generated by the flow is masked by the sound of hypernasality. Although inaudible, the effects of nasal emission with a large opening include weak or omitted consonants, the need to take more frequent breaths to sustain phonation for connected speech, and the potential for development of compensatory productions to increase intelligibility (Peterson-Falzone et al. 2016).

As the size of the VP opening is reduced, so is the coupling of the oral and nasal cavities. While undesired sound from the vocal tract resonates less in the nasal cavity, the nasal emission becomes more audible. The increase in the perceived audibility of nasal emission is presumed to be from the increased flow resistance (in the nasal cavity) and the reduction in dominance of hypernasality (McWilliams et al. 1990).

A small VP opening can produce nasal emission that is quite audible and can be very loud and distorting, making speech unpleasant to hear and often unclear (Kummer et al. 1992, 2003; Peterson-Falzone et al. 2016). This severe form of audible nasal emission is commonly known as *nasal turbulence*. The formation of turbulence and its sound in the nasal cavity have been described as occurring when the airflow accelerates through the small VP opening and is then discharged into an expansion in the nasal cavity (Hixon et al. 2014). Furthermore, in a previous study (Sundström and Oren 2019a), an unsteady shear layer interface from a jet was found to be the principal mechanism for the turbulence production in the nasal cavity, whereas the flow acceleration through the VP valve was found to reduce the turbulence intensity.

Previous studies that have aimed to investigate the relation of VP opening to speech disorders were mostly focused on nasality. Using indirect measurement of the opening size,

(Dalston et al. 1991) showed weak correlation between the estimated size of the opening and the measured nasalance and the perceived nasality. On the other hand, when using perceptual measures for the VP opening, (Kummer et al. 2003) showed that nasal rustle and hypernasality were typically correlated with small and large VP openings, respectively. In a more recent study, (Bunton 2015) used a computational model to systematically change the nasalance based on the size of the VP opening during a sustained vowel. Her study found that the area of the VP opening needs to exceed 10 mm^2 for listeners to detect nasality. None of these aforementioned studies have considered how nasal emission—in particular, its aeroacoustic mechanisms that can also produce undesired sound in the nasal cavity—change as a function of VP opening.

In summary, when there is a large velopharyngeal opening, hypernasality is the predominant characteristic of speech, whereas nasal emission is inaudible. When the opening is small, nasal emission is the predominant characteristic of speech, whereas resonance is normal. A mid-size opening can be characterized by both acoustic features. It is unclear how changes in the VP opening size affect the flow characteristics and aeroacoustics mechanisms of nasal emission. The aim of the current study is the first step towards understanding these relations by investigating how a systematic change in the size of the VP opening affects the flow characteristics in a patient-specific model that is based on a sibilant sound.

2 Method

The model in this study is based on cases of modifying the geometry of the VP valve opening from our previous work (Sundström and Oren 2019a). The geometry for the baseline case was based on an 8-year-old boy who was diagnosed with severe nasal emission that occurred on all oral sounds (Fig. 1). Using nasopharyngoscopy by a speech-language pathologist (SLP) who specializes in cleft palate, resonance disorders, and VPI, the VP opening was perceived to be small.

The delineated baseline case was based on CT scans that were taken while the subject was sustaining the sound /z/. Voicing by the subject was needed in order to ensure correct timing of the CT scans. The subject was asked to sustain the sound for as long as he could and the scans (which lasted less than 500 msec) were initiated about 1–2 seconds after the subject had begun voicing. The /z/ sound was selected because it is a homorganic cognate of /s/, which is the continuant fricative sound where nasal emission is most prominent. Further details on the CT scan procedure and the digital 3D reconstruction can be found in (Sundström and Oren 2019a).

The opening in the VP valve was lateral to the medial plane and the modification to its geometry was done by increasing or reducing the opening length in the medial dimension. The widening was done by systematically increasing the opening to be 2, 4, and 8 times wider in the medial direction (designated as 2x, 4x, and 8x, respectively) while keeping the gap between the velum and the posterior pharyngeal wall constant, as if elongating a slot. The narrowing was done by systematically decreasing the width of the opening in the lateral direction to be one half or one-quarter of the baseline case (designated as 0.5x and 0.25x, respectively). In addition to widening and narrowing of the VP opening, a case simulating

full VP closure was also included by extending the velum to the posterior and lateral pharyngeal walls. Other than the modifications to the size of the VP opening, the geometry everywhere was kept the same between the cases (Fig. 2).

The inlet for the model was defined in the trachea about 2 cm below the glottis (blue arrow in Fig. 1a) to have a stagnation pressure corresponding to 6 cmH₂O for all cases. The inlet pressure was adopted from physiological pressure measurements according to (Ladefoged 1963). The outlet was defined on the surface of the hemisphere (Fig. 1b) and applied with an acoustically free stream condition and standard atmospheric pressure. To minimize acoustical reflections, the outlet boundary was positioned at a large radial distance, $R=0.7$ m, from the subject's face. Other boundary conditions assumed no-slip wall conditions. A summary of the Reynolds numbers (Re), Mach numbers (Ma) and reference velocities at the inlet, VP valve and oral constriction are presented in Table 1. The equivalent diameter for the VP opening is defined as $D_e = \sqrt{4A/\pi}$ where A is the cross-sectional area at the narrowest VP valve section (Fig. 2).

The compressible Reynolds-Averaged Navier-Stokes (RANS) equations along with the Realizable $K-\epsilon$ equations for turbulence closure were solved numerically using the CFD software STAR-CCM+. The rationale for using compressible N-S equations was to provide a smooth transition between RANS and Large Eddy Simulation (LES) computation (Sundström and Oren 2019b). Compressible LES and a large hemispherical domain have been adopted in a follow-up study with the aim to quantify the far-field sound spectrum. The Reynold's decomposition was considered applicable for the current study because the inlet flow is steady, and fluctuations are relatively moderate compared to the averaged bulk flow. After Reynold's decomposition, the governing equations for mean mass, momentum, and energy transport can be formulated as (Ferziger and Peri 2012):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \mathbf{U}) + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = -\nabla \cdot P \mathbf{I} + \nabla \cdot (\bar{\mathbf{T}} + \mathbf{T}_{RANS}) \quad (2)$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho E \mathbf{U}) = -\nabla \cdot P \mathbf{U} + \nabla \cdot (\bar{\mathbf{T}} + \mathbf{T}_{RANS}) \mathbf{U} - \nabla \cdot \bar{\mathbf{q}} \quad (3)$$

where ρ is the density, $\mathbf{U}$ is the mean velocity, P is the mean pressure, $\mathbf{I}$ is the identity tensor, $\bar{\mathbf{T}}$ is the mean viscous stress tensor, E is the mean total energy per unit mass, and $\bar{\mathbf{q}}$ is the mean heat flux. The main difference compared to the original Navier-Stokes equations is the additional stress tensor $\mathbf{T}_{RANS}$. This term is modeled using the Boussinesq approximation so that a turbulent eddy viscosity μ_t maybe computed from mean flow quantities:

$$\mathbf{T}_{RANS} = 2\mu_t \mathbf{S} - \frac{2}{3}(\mu_t \nabla \cdot \mathbf{U}) \mathbf{I} \quad (4)$$

where $\mathbf{S}$ is the mean strain rate tensor. Two-equation turbulence models are a cost-effective approach in applied fluid mechanics applications to provide closure relations of the RANS equations (Sundström and Tomac 2019). In this study, the eddy viscosity model Realizable K - ϵ is used where two additional scalar transport equations for the turbulent kinetic energy K and eddy dissipation rate ϵ enable estimation of μ_t (Shih et al. 1995). Using eddy viscosity modeling for turbulence closure was based on our previous study that showed development of a thin shear layer just downstream of the VP valve in case of the baseline model (Sundström and Oren 2019a). This is a flow feature for which the two-equation eddy viscosity model Realizable K - ϵ has been calibrated (Bechara et al. 1994).

Acoustic sources were predicted using the broadband models of (Curle 1955) and (Proudman 1952). In Curle's model, the noise due to pressure fluctuations on solid boundaries is accounted as surface dipole acoustic sources and the local contribution to the surface acoustic power SAP per unit area is computed via the surface integral:

$$SAP = \int_S \frac{1}{(12\rho_0\pi c_0^3)} \overline{\left(\frac{\partial p}{\partial t}\right)^2} dS(\mathbf{y}) \quad (5)$$

where ρ_0 is the far-field density, c_0 is the speed of sound in the far-field, and $\mathbf{y}$ is the coordinate where the noise is evaluated. The mean-square time derivative of the surface pressure fluctuation is assumed to be proportional to the wall shear stress (Hinze 1975).

In Proudman's model, noise due to volume fluctuations via isotropic turbulence is accounted as quadrupole acoustic sources where the acoustic power AP per unit volume is computed as:

$$AP = C_a \rho_0 \frac{u^8}{l c_0^5} \quad (6)$$

In this expression, the characteristic velocity of the eddy fluctuations is estimated as $u = \sqrt{2K/3}$, where turbulent kinetic energy K is obtained from the eddy viscosity modeling, and l is the characteristic turbulent mixing length scale. The constant C_a is according to the broadband correlation done by (Sarkar and Hussaini 1993).

While both models correlate turbulence-generated flow noise with acoustic sources, they lack mechanisms for identifying coherent flow structures and quantifying frequency information. Nevertheless, their advantage is that they can utilize data from steady-state RANS, which is computationally efficient for quantification of strength and type of the acoustic source.

2.1 Model verification and validation

Model verification was done by means of a grid dependency study (Fig. 3). Four grids with a factor two refinement in between grid levels were tested. The mass flow through the VP valve for the baseline case (1x) was used as an integral property for the verification. Richardson's extrapolation was used for evaluating the error with respect to the infinite grid

solution $\Delta x = 0$ mm. For each grid refinement order, the error reduced monotonically two orders of magnitude, which coincided with the 2nd order accuracy of the numerical scheme. Therefore the fine grid with average edge length $\Delta x = 0.25$ mm was used for the subsequent analysis.

The computational model was validated by comparing the predicted velocity with velocity measurements that were taken using particle image velocimetry (PIV). The PIV measurements were made in a silicone model that was based on the same baseline geometry with $Re_{VP} = 5500$. The details of this experimental study are discussed in (Rollins and Oren 2019). Velocity profiles were extracted in the oropharynx, the VP valve, and the nasopharynx by approximating the same location in the computational and experimental data (Fig. 4).

There is a good agreement with the velocity measurements in the bulk flow regions. The difference in the normalized velocity profiles in this region of the flow is in the order of 5–10%. A deviation was observed in the nasopharynx, in particular with the location of the developed profile (dashed lines in Fig. 4). The difference in the normalized location of the peak velocity of the exiting jet between the measurement and the numerical data is in the order of 8%. One reason for this difference might be the uncertainty in the position and orientation of the line profiles that were used for extraction of the experimental data from PIV. Another reason for the difference might be that the applied boundary conditions in the numerical model were different than the experimental set-up. Inevitably, there are probably also small differences in the geometry of the baseline models due to the uncertainty/accuracy of the 3-D printing process that was used to generate the silicone model. A larger difference with the PIV measurements is also observed near the walls where it is known that PIV measurements cannot resolve a boundary layer near a wall very well (Kähler et al. 2012).

3 Results

Qualitative inspection of the flow fields shows that in all cases of VP opening, a distinct jet feature develops in the posterior nasal cavity (Fig. 5). The velocity contours from each case are shown for the region of the VP valve in the sagittal plane (see Fig. 1 for location) and for three cross-sectional planes that are located by the entrance to the VP valve (oropharynx), most constricted area of the valve (VP valve), and in the nasopharynx. In the case of a closed VP (0x), no flow passes through the VP port; hence, the flow in the posterior nasal cavity is stagnant.

When a small opening is introduced, a jet develops with the highest velocity magnitude exposed at the minimum cross-sectional area of the VP valve. Upstream of the minimal cross-sectional area, the streamlines approach each other, which means that the flow accelerates through the constriction. This trend is kept for the other cases as the size of the VP opening is systematically increased; however, velocity within the VP valve is decreased (Table 1). This inverse relationship between flow velocity and the size of the VP opening follows Bernoulli's principle. Downstream of the minimal cross-sectional area, the distance between streamlines widens from one another, which indicates that the flow decelerates as it

enters the nasopharynx. The widening of the streamlines is proportional to the size of the VP opening. The streamlines also reveal that large-scale vortical structures form in the posterior nasal cavity, including two local areas in the nasopharynx of reversing flow.

Some similarities in velocity profiles were observed when the streamwise velocity component was plotted as a function of the VP opening for the cross-sectional areas in the oropharynx, VP opening, and nasopharynx (Fig. 6). The approximate location of these profiles is marked on the baseline velocity contour in Fig. 5. Qualitatively, the velocity profiles show similar distributions between the different cases at each axial location, but some specific observations can be made. The profiles in the oropharynx (Fig. 6a) show that the slope at the center increases as the opening size increases. This means that the distribution becomes less uniform and the air velocity is locally higher closer to the pharyngeal wall as opposed to velum. The profiles in the VP valve (Fig. 6b) show that the average velocity has increased by approximately a factor of two as compared to the profiles in the oropharynx (Fig. 6a), which is due to the reduction in cross-sectional area. The curves from the cases where the opening is widened are almost overlapping, indicating approximate similarity when the maximum velocity U_{max} is considered for normalization. The profiles in the nasopharynx (Fig. 6c) show jet profile characteristics in all cases. However, the baseline case (1x) has a narrower jet width compared to the larger VP openings. The nasopharyngeal profiles also show that the flow seems to separate from the pharyngeal wall in the 1x, 2x, 4x, and 8x cases, and that the center of the jet moves towards the pharyngeal wall as the size of the opening is decreased. These observations can also be appreciated in the cross-sectional velocity contours that are shown for this location in Fig. 5.

The coupling with the nasal cavity when the VP is open changes the dynamics of the pharyngeal flow significantly because of the presence of the bifurcation at the oropharynx. The (incompressible) flow behavior is not only changed upstream of the bifurcation (e.g., in the pharynx), but also downstream right outside of the lips and nostrils where the oral and nasal jets are merging. The current study shows that increasing the size of the VP opening does not change the flow behavior, but rather its magnitude; no new flow mechanisms are formed as the size of the VP opening is increased. However, the magnitude of the velocity and turbulence are decreased.

The change in turbulence, specifically in the posterior nasal cavity, is shown using the turbulent kinetic energy (TKE), which is obtained using the eddy viscosity model (Jones and Launder 1972; Rodi 1991). As the severe form of nasal emission is attributed to the undesired turbulence in the nasal cavity, it is important to specifically assess how turbulence distribution changes as a function of the VP opening. The distribution of the TKE between the different cases shows some noticeable difference in magnitude (Fig. 7). Two distinct bands with elevated TKE levels can be seen in the sagittal plane in all cases except 0x. The cross-sectional contour for the TKE distribution in the nasopharynx resembles a ring-shaped feature, which correlates with typical jet configurations. The size of the ring-shaped feature increases as the velopharyngeal size increases. The non-symmetrical distribution of the TKE stems from the irregular geometry of the opening where the airflow is discharged into the posterior nasal cavity.

As with velocity, TKE profiles are extracted at the same locations for all cases (Fig. 8). At the entrance to the VP valve (oropharynx–Fig. 8a), the TKE level is relatively moderate and similar in all cases, except for the 0.5x and 0.25x cases. The profiles are relatively round at the center and increase slightly when a larger VP opening is considered. At the narrowest cross-sectional area inside the VP valve (Fig. 8b), the absolute TKE level is relatively unchanged from the oropharynx. In the nasopharynx (Fig. 8c), the profiles become wider, which correlates with the fact that the jet spreads out more for the larger VP openings. In the decay region of the jet (Fig. 8c), the profiles for the 0.5x and 0.25x show a distinct peak in the middle, which characterizes similarity.

3.1 Flow and acoustic characteristics as a function of the VP opening size

The effects of changing the size of the VP opening on the current model can be appreciated by plotting some of the flow characteristics along the streamwise direction of each model (Fig. 9). Each flow parameter that is shown is based on the average or maximum values at each cross-sectional area along the centerline. The locations of the oropharyngeal, VP, and nasopharyngeal planes that were shown previously are also marked on the figure.

The distribution for the averaged static pressure (Fig. 9a) shows that a pressure drop occurs following each constriction in the model. Downstream of the VP valve, the static pressure in the nasal cavity is always zero. The magnitude of the static pressure distribution along the centerline is inversely proportional to the size of the opening; the highest pressure values are observed in the fully closed VP case while the lowest values are observed in the 8x. This difference between cases is expected because the VP valve increasingly serves as a release valve for the pressure as its size increases.

The values for the maximum velocity (Fig. 9b) along the model show three distinct peaks that correspond to the constrictions at the glottis, VP valve, and the lingual-alveolar articulation of the sibilant sound. The highest values of the velocity are predicted in the VP valve for the most constricted cases (0.5x and 0.25x). Each acceleration of the flow corresponds to an increase in turbulence (Fig. 9c) that occurs due to the increase in inertial forces (i.e., velocity) and the sudden increase in cross-sectional area.

The wall shear stress (WSS) also shows three elevated regions (Fig. 9d). WSS is sometimes considered a good predictor for acoustic sources because it is a measure of wall bounded shear layer, which is a region where sound can be generated. The WSS plots match well with the plots for the acoustic source contribution associated with turbulent fluctuation that interacts with viscous walls, which are predicted by Curle's equation (Fig. 9e). These fluctuations are associated with a dipole source term. Both of these plots show significant peaks just past the constrictions in the glottis, VP valve, and oral constriction. Using the maximum acoustic power predicted by Curle's equation shows that the dipole source contribution is decreased as the size of the VP opening is increased. In addition, secondary peaks are predicted in the pharynx and the nasal cavity. The latter is in the turbinate region, where the geometry is characterized by thin passages and large surface areas.

The distribution of the sound source that considers only volume fluctuations using Proudman's equation also shows three distinct peaks that match the locations of the

turbulence peaks (Fig. 8f). The volume fluctuations are associated with quadrupole source terms and in all cases are about two orders of magnitude less than the dipole source terms.

The flow resistance in the current models changes linearly with the size of the VP opening (Fig. 10). Flow resistance (for a gas) is typically defined using Ohm's law as the ratio between the pressure drop and the flow rate. The flow resistance across the VP valve decreases with the increase of VP opening size as approximately $\sim 1/D_e^2$. The flow resistance over the oral constriction is also included and approach a constant value as $D_e \rightarrow 0$ since the cross-section area is constant, and reduces with larger VP openings.

The change in turbulence is also linear with respect to the size of the VP opening. Plotting the maximum value of TKE in each location of the nasopharyngeal profiles (Fig. 10b) shows inverse proportionality of approximately $1/D_e$ as the size of the opening is increased from the baseline (i.e., 1x to 8x). However, as the size of the VP opening approaches a closed state, TKE begins to drop because of the increased flow resistance and rapid decay of the jet. For these small openings, the TKE increases approximately proportional to D_e^2 .

4 Discussion

The present study investigates how flow mechanisms in the vocal tract change as a function of VP opening size during production of a sibilant sound. The results show that unlike in a case with a fully closed VP where the majority of turbulence (and subsequently its sound) is produced at the oral constriction, an opening of the VP valve affects the flow characteristics due to the coupling with the nasal cavity. The characteristics of the nasalized flow depend on the size of the VP opening. At the VP valve, flow characteristics such as velocity, turbulence, and WSS are inversely proportional to the size of the opening. Above a critical size of the VP opening, the nasopharyngeal turbulence decays as approximately $1/D_e$. Finally, the current study shows that the majority of the sound that is produced by turbulence is generated by dipole source mechanisms, which is in agreement with what other studies have suggested for the sound source mechanisms for sibilant sounds during normal speech (Shadle 1991; Krane 2005).

It is interesting to note that except with the largest VP opening considered (8x case), small TKE peaks are observed near the VP valve walls, which could indicate development of a boundary layer (Fig. 8b). The ratio of the VP valve length over its equivalent diameter is in the order of $L/D_e \approx 6$ for the baseline case (1x). However, for turbulent pipe flow to become fully developed, it would typically require a longer hydrodynamic entrance length, i.e. $L/D_e \approx 10$ (Cimbala and Cengel 2003). Other authors advocate entrance lengths beyond 100 (Lien et al. 2004). The biggest difference in TKE between cases is shown in the nasopharynx (Fig. 8c). At this location, all TKE profiles, except for the 0.5x and 0.25x cases, show two peaks that coincide with the unsteady shear layer interface of the jet. These profiles also coincide with the inflections in the velocity profiles (see Fig. 6c). When the size of the VP opening increases beyond 1x, the peak TKE in the posterior nasal cavity is reduced. Thus, at the location that is shown in the nasopharynx, the jets for the baseline and the wider cases are fully developed, while the jets for the narrower openings are already decaying. This

observation also explains why the narrower cases show higher velocity in the middle of the VP valve (Fig. 6b) than in the nasopharynx (Fig. 6c).

The reduction in turbulence and subsequently the magnitude of the dipole sources is likely to also affect the acoustic characteristics in the far-field. Tonalities that are formed in the posterior nasal cavity with small VP openings can be detected in the far-field. However, these aeroacoustic mechanisms disappear for large VP openings, where no tonalities (from the posterior nasal cavity) are detected in the far-field. Further work is needed to determine the change in the far-field acoustic spectrum as the size of the VP valve is systematically changed.

Sibilant sounds are produced by constricting part of the vocal tract, which leads to a pressure building up behind the obstruction. Any opening of the VP valve will then act as a release valve for the pressure, thus distorting the sound. It was found that the static pressure in the nasal cavity attains equilibrium with the atmospheric pressure. This is an important observation that supports the assumption that the static pressure in the nasal cavity is atmospheric, which is used with the Perci Sars aerodynamic assessment of speech for estimating the VP opening area (Warren 1979). If the VP opening is larger than the size of the oral constriction during a sibilant sound, the majority of the airflow will be directed towards the nasal cavity. In addition to loss of airflow through nasal emission, the oral pressure buildup is also reduced with larger VP openings, which can produce deficiencies in speech quality. This reduction in oral pressure is shown in the pressure distribution for the 2x, 4x, and 8x cases compared with the 0x case (Fig. 9a). As a result, the strength of possible aeroacoustic mechanisms, as predicted by the Curle and Proudman models (Figs. 9e–f), are generally also lower, which might suggest why nasal emission is typically inaudible in cases with large VP opening. In addition, the surface fluctuation associated with dipole source terms was calculated to be two orders of magnitude larger than the quadrupole source terms (Fig. 9f). This suggests that the sound mechanism in the current model is a close analog with dipole acoustic sources and that the quadrupole contribution is negligible.

The sudden increase in the cross-sectional area in the nasopharynx introduces a secondary peak in turbulence production in the nasal cavity (Fig. 9c). The increases in maximum velocity and turbulence are inversely proportional to the size of the VP opening. It is also interesting to note that the magnitude of the peak velocity at the oral constriction, U_{oral} , is at a similar magnitude to the peak velocity in the VP valve even though the size of the oral constriction remains constant (Fig. 9b). This is because the pressure upstream to the oral and VP constriction is always the same (see Fig. 9a). The swift reduction in velocity and TKE from the VP valve to the nasopharynx that is shown for the narrower cases occurs due to the rapid decay of their respective jets.

The approximate change in nasal turbulence as $1/D_e$ suggests that the possible contribution from turbulence to the undesired sound in the nasal cavity is gradually reduced as the size of the VP opening is increased. This observation suggests that reducing the size of a large opening would have a negligible effect on turbulence if the size of the opening remains “large”. Such circumstances may occur by the natural growth of a subject; the size of the VP opening can be reduced as more tissue mass is built around the pharyngeal walls and the

velum. The current study shows that the TKE in the nasopharynx would increase only slightly when the cross-sectional area is reduced from 8x to 4x. Thus, nasal emission, which is typically inaudible with a large VP opening, would likely remain inaudible if the reduction of the VP opening is not sufficient. In addition, based on the study of (Bunton 2015), nasality, which will mask nasal emission, is expected to be detected for $D_e > 3.6$ mm in the current model.

The inverse approximation of turbulence magnitude to $1/D_e$ also indicates that as the opening becomes smaller and smaller, nasal turbulence (and its sound contribution) would increase significantly. Hence, any small change in the size of “small” VP opening can have a significant effect on the turbulence in the nasal cavity. As the size of the VP opening is decreased, the strength of possible aeroacoustic mechanisms in the nasal cavity is increased, thus making it more likely that nasal emission would be perceived as audible. It is not clear from the current study at what point the transition from inaudible to audible sound may occur, especially considering the audibility is perceptual in nature and cannot be predicted using the current computational technique.

The inverse relationship between the size of the VP opening and aeroacoustic mechanisms can explain why in some cases patients who are diagnosed with hypernasality and large VP opening can develop severe audible nasal emission (i.e., nasal turbulence) if a small VP opening is left after a surgical procedure.

During a sibilant sound, the relationship between the strength of possible aeroacoustic mechanisms and the VP opening size may ultimately depend on the size of the oral constriction. As long as the size of the VP opening is larger than the oral constriction, the majority of the airflow from the lung will follow the ‘path of least resistance’ to become nasal emission. The current model predicts that turbulence in the nasal cavity would exponentially increase as the VP opening size is decreased. On the other hand, once the VP opening is smaller than the oral constriction, the majority of the airflow would enter the oral cavity as the resistance in the VP valve is now higher (Fig. 9a). This is a very interesting observation because it indicates that flow resistance changes much more significantly for small VP openings (where $D_e \rightarrow 0$). The flow resistance across the oral constriction is also affected by the size of the VP opening. The size of the oral constriction is constant in the current model; thus any change in resistance stems from the changes in the VP valve, which is located upstream. As more flow passes through the VP valve when its size is widened from the baseline, the flow resistance across the oral constriction reduces. As the size of the VP opening is decreased from the baseline, the resistance across the oral constriction is lower than the VP valve and asymptotes towards its value when the VP valve is fully closed. Thus, as the VP opening becomes smaller and smaller, the resistance across it is higher than the oral constriction and asymptotes towards infinity. The crossing over between the higher/lower resistance values occurs when the oral and VP valve have the same minimal cross-sectional area (at $D_e = 2.1$ mm in the current model). In this case, the model acts as a duct where the flow rate is equal through both constrictions.

The relationships that are shown in Fig. 10a with D_e^2 for small openings and $1/D_e$ for larger openings suggest that there is a critical size for the VP opening where the TKE will be at its

maximum. The current model predicts that this occurs when the minimal cross-sectional areas for the VP valve and oral constriction are equal. The current model also predicts that turbulence (and likely the sound it produces) exponentially increases as the VP opening size decreases. On the other hand, if the VP opening is smaller than the oral constriction, the majority of the airflow would enter the oral cavity since the resistance in the VP valve is higher. In the current model, the reduction in turbulence in the nasopharynx for VP openings that are smaller than the oral constriction occurs by a much higher rate compared with the turbulence reduction for VP openings that are larger than the oral constriction (Fig. 10b). The fast reduction in turbulence, and subsequently in its aeroacoustic mechanisms, will likely reduce the audibility characteristics (i.e., frication sound) of nasal emission.

The theory on the likelihood for nasal emission to be perceived as audible or inaudible based on the area ratio of the VP opening and oral constriction can be imperative for determining whether the VP opening is considered 'large' or 'small'. Based on discussion with clinicians, it seems that they find it easier to agree that an opening is 'large' than that it is 'small'. The current study suggests that the VP opening should be categorized based on its size relative to the oral constriction. If the size is smaller than the oral constriction, although nasal emission would still exist, it is less likely to be audible or severe.

The categorization of the VP opening size relative to the oral constriction during sibilant sound can be interesting for clinicians because it suggests that surgery may not be the only way to resolve undesired sound in the nasal cavity in case of small VP opening. Clinicians may consider therapy or the 'wait and see' approach to see if the size of the VP opening can be reduced just enough to have a significant impact on the turbulence and subsequently its sound that is formed in the nasal cavity. Although a small opening would be left, it may be small enough to act as a full closure of the VP valve.

4.1 Limitations

The systematic change in the size of the VP opening is done with the assumption that the closure of the VP valve occurs in a coronal pattern. Other closure patterns of the VP valve (e.g., sagittal, circular, etc.) would yield different geometry of the opening, which in turn would affect the flow behavior, specifically in the posterior nasal cavity. It is unlikely that the conclusions of the current study (e.g., the inverse relation of VP opening size with turbulence magnitude and dipole source contribution) would change. However, differences in flow behavior can affect the acoustic spectrum by changing the sound source mechanisms. The difference in the acoustic spectrum can be perceived differently by a listener in the far-field.

Both Curle's and Proudman's equations fall in the category of broadband acoustic correlation models. Therefore, there are several simplifications that limit the applicability and none of the models take into account specific frequencies that may exist during the sound generation process. Temporal flow fluctuations that may occur due to convection of eddy vortices were not correlated with the broadband noise. The steady-state approach in the RANS framework means that fluctuations are small in relation to the average bulk flow, which limits the analysis to simple sibilant sounds. Simulation of a more composite sound suggests a transition to a dynamic numerical procedure, such as Large Eddy Simulation

(Sundström et al. 2018b, a), that may quantify turbulence production in specific speech sound categories, such as fricatives and plosives.

Acknowledgments

The authors acknowledge the support of NIH Grant No. K25DC014755.

References

- Bechara W, Lafon P, Bailly C, Candel S (1994) Application of a k-epsilon turbulence model to the prediction for simple and coaxial free jets. *J Acoust Soc Am* 97:3518–3531. doi: 10.1121/1.412438
- Bunton K (2015) Effects of Nasal Port Area on Perception of Nasality and Measures of Nasalance Based on Computational Modeling. *Cleft Palate-Craniofacial J* 52:110–114. doi: 10.1597/13-126
- Cimbala YA, Cengel JM (2003) Fluid mechanics : fundamentals and applications (1st ed.)
- Curle N (1955) The Influence of Solid Boundaries upon Aerodynamic Sound. *Proc R Soc A Math Phys Eng Sci* 231:505–514. doi: 10.1098/rspa.1955.0191
- Dalston RM, Warren DW, Dalston ET (1991) Use of nasometry as a diagnostic tool for identifying patients with velopharyngeal impairment. *Cleft Palate-Craniofacial J* 28:184–189
- Ferziger JH, Peri M (2012) Computational Methods for Fluid Dynamics, 3rd rev. Springer-Verlag, Berlin.
- Hinze JO (1975) Turbulence, 2nd Editio. MacGraw-Hill, New York
- Hixon TJ, Weismer G, Hoit JD (2014) Preclinical speech science: Anatomy, physiology, acoustics, perception
- Jones WP, Launder BE (1972) The prediction of laminarization with a two-equation model of turbulence. *Int J Heat Mass Transf* 15:301–314. doi: 10.1016/0017-9310(72)90076-2
- Kähler CJ, Scharnowski S, Cierpka C (2012) On the uncertainty of digital PIV and PTV near walls. *Exp Fluids* 52:1641–1656. doi: 10.1007/s00348-012-1307-3
- Krane MH (2005) Aeroacoustic production of low-frequency unvoiced speech sounds. *J Acoust Soc Am* 118:410–427. doi: 10.1121/1.1862251 [PubMed: 16119362]
- Kummer AW, Briggs M, Lee L (2003) The Relationship between the Characteristics of Speech and Velopharyngeal Gap Size. *Cleft Palate-Craniofacial J* 40:590–596
- Kummer AW, Curtis C, Wiggs M, et al. (1992) Comparison of Velopharyngeal Gap Size in Patients with Hypernasality, Hypernasality and Nasal Emission, or Nasal Turbulence (Rustle) as the Primary Speech Characteristic. *Cleft Palate-Craniofacial J* 29:152–156
- Ladefoged P (1963) Some Physiological Parameters in Speech. *Lang Speech* 6:109–119. doi: 10.1177/002383096300600301
- Lien K, Monty JP, Chong MS, Ooi A (2004) The entrance length for fully developed turbulent channel flow. In: 15th Australasian Fluid Mechanics Conference (Sydney, Australia)
- McWilliams BJ, Morris HL, Shelton RL (1990) Cleft palate speech. Mosby Elsevier Health Science
- Peterson-Falzone SJ, Trost-Cardamone J, Karnell MP, Hardin-Jones MA (2016) The Clinician's Guide to Treating Cleft Palate Speech-E-Book. Elsevier Health Sciences
- Proudman I (1952) The Generation of Noise by Isotropic Turbulence. *Proc R Soc A Math Phys Eng Sci* 214:119–132. doi: 10.1098/rspa.1952.0154
- Rodi W (1991) Experience with two-layer models combining the k-epsilon model with a one-equation model near the wall. In: 29th Aerospace Sciences Meeting, AIAA 91–0216
- Rollins M, Oren L (2019) Aerodynamic flow variables as a function of velopharyngeal gap size. 177th Meet Acoust Soc Am 36:060001. doi: 10.1121/2.0001022
- Sarkar S, Hussaini MY (1993) Computation of the sound generated by isotropic turbulence
- Shadle CH (1991) The effect of geometry on source mechanisms of fricative consonants. *J Phonet* 19:409–424

- Shih TH, Liou WW, Shabbir A, et al. (1995) A New K-epsilon Eddy Viscosity Model for High Reynolds Number Turbulent Flows: Model Development and Validation. *Comput & Fluids*. doi: 10.1016/0045-7930(94)00032-T
- Sundström E, Oren L (2019a) Pharyngeal flow simulations during sibilant sound in a patient-specific model with velopharyngeal insufficiency. *J Acoust Soc Am* 145:3137–3145. doi: 10.1121/1.5108889 [PubMed: 31153316]
- Sundström E, Oren L (2019b) Sound production mechanisms of audible nasal emission during the sibilant /s/. *J Acoust Soc Am* 146:4199–4210. doi: 10.1121/1.5135566 [PubMed: 31893718]
- Sundström E, Semlitsch B, Mih escu M (2018a) Acoustic signature of flow instabilities in radial compressors. *J Sound Vib* 434:221–236. doi: 10.1016/j.jsv.2018.07.040
- Sundström E, Semlitsch B, Mih escu M (2018b) Generation Mechanisms of Rotating Stall and Surge in Centrifugal Compressors. *Flow, Turbul Combust* 100:705–719. doi: 10.1007/s10494-017-9877-z
- Sundström E, Tomac M (2019) Synchronization and Flow Characteristics of the Opposed Facing Oscillator Pair in Back-to-Back Configuration. *Flow, Turbul Combust* 1–17. doi: 10.1007/s10494-019-00064-6
- Warren DW (1979) Perci: a method for rating palatal efficiency. *Cleft Palate J* 16:279 [PubMed: 287577]

Fig. 1.

Geometry for the computational models. a) Baseline geometry delineated from the subject sustaining a sibilant sound. b) Overview of computational control volume where $R = 0.7 \text{ m}$ is the radius of the hemispherical domain. c) Zoomed-in isometric views of the VP valve region (indicated by the dashed square in the baseline geometry) showing the systematic increase in opening size: 0x (VP closed), 0.25x, 0.5x, 1x (baseline), 2x, 4x, and 8x. The VP valve was modified by changing its cross-sectional area, which is shown in Fig. 2.

Fig. 2.

Differences in the cross-sectional area from the levels of the oropharynx to the nasopharynx. Zero along the abscissa marks the location for the minimum cross-section area inside the VP valve. Outside the VP valve, the geometry in all cases was kept the same.

Fig. 3.

Grid dependency assessment based on integrating the mass flow at the minimum constriction of the VP valve ($x = 0$ mm, see Fig. 2). The error is computed with respect to the infinite grid solution that was obtained using Richardson's extrapolation (Richardson, 1911). For each grid refinement order the error reduces two orders of magnitude.

Fig. 4.

Comparison of streamwise velocity (U) profiles for the baseline models. The approximate location of the line profiles in the oropharynx, VP valve, and the nasopharynx are indicated in the small image to the left. Velocity profiles are normalized with the maximum velocity ($U_{max} = 3.2$ m/s and 29.4 m/s for the experimental and numerical data, respectively). The span of each profile is normalized by its length (D) where $y/D = 0$ is on pharyngeal wall and $y/D = 1$ is on the velar wall.

Fig. 5.

Velocity distributions for all considered cases are shown using constrained streamlines in the sagittal and selected cross-sectional planes. The streamlines are colored based on the velocity magnitude. The lines on the sagittal plane for the baseline case (1x) indicate the approximate position for the cross-sectional planes.

Fig. 6.

Streamwise velocity profiles shown for different sizes of VP openings within the a) oropharynx, b) VP valve, and c) nasopharynx. The approximate locations of the profiles are marked in Fig. 4. The velocity profiles are normalized with the maximum axial velocity at the VP valve ($U_{\max}$) and the span of the profile (D).

Fig. 7. Turbulence kinetic energy (TKE) distribution for all cases. Planes shown are the same as in Fig. 5.

Fig. 8. Turbulent kinetic energy (TKE) profiles for the same locations as Fig. 7 within the a) oropharynx, b) VP valve, and c) nasopharynx.

Fig. 9.

Distribution of flow characteristics along the centerline of the model as a function of VP opening size. a) Mean static pressure. b) Maximum velocity magnitude. c) Maximum turbulent kinetic energy. d) Maximum wall shear stress. e) Maximum Curle's Acoustic Power, and f) Maximum Proudman's Acoustic Power.

Fig. 10.

a) Change in flow resistance across the VP. The solid line is a power curve fit with a coefficient of determination $r^2 > 0.9$. b) The maximum turbulent kinetic energy in the nasopharynx as a function of the equivalent diameter for the VP opening. Cases 0x, 0.25x, and 0.5x are fitted with a polynomial curve ($r^2 > 0.9$), and the larger opening cases are fitted with a power curve ($r^2 > 0.9$).

Table 1

Summary of boundary conditions and local reference parameters for all cases. $Re = UD_e/\nu$, with U – bulk velocity and ν – kinematic viscosity of air at 300 K. $Ma = U/c$, where c – speed of sound.

Case	D_e (mm)	P_{0in} (Pa)	P_{out} (Pa)	Ma_{in} (-)	Re_{in} (-)	U_{in} (m/s)	Ma_{VP} (-)	Re_{VP} (-)	U_{VP} (m/s)	Ma_{oral} (-)	Re_{oral} (-)	U_{oral} (m/s)
0x	0	588.6	0	0.01	1600	5	N/A	N/A	N/A	0.10	4420	33
0.25x	1.3	588.6	0	0.02	2040	6	0.07	2120	26	0.09	4090	32
0.5x	1.7	588.6	0	0.02	2520	8	0.08	3080	28	0.09	3960	31
1x	2.3	588.6	0	0.03	3100	10	0.08	4150	27	0.09	3870	30
2x	3.4	588.6	0	0.04	4200	13	0.07	4960	22	0.07	3200	24
4x	4.2	588.6	0	0.05	5000	15	0.06	5290	19	0.06	2620	20
8x	4.8	588.6	0	0.05	5390	16	0.05	5170	16	0.04	2040	16