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Quantification of the intraglottal pressure induced by flow separation vortices using large eddy simulation

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Abstract

The greatest rate of change in the glottal flow rate during phonation is a rapid decrease that occurs during the latter part of the glottal closing. Previous works showed that intraglottal flow separation vortices (FSVs) form in a divergent glottis, produce negative gauge pressures (below atmospheric) during closing. It is hypothesized here that FSVs contribute to the rapid closing mechanism of the true vocal folds during phonation.

Four idealized static models (M5) of the human larynx were investigated using large eddy simulation (LES): 2 models featured parallel folds that did not enable flow separation in the glottis and 2 models involved a divergent glottis. The influence of the ventricular gap (narrow/wide) is evaluated. An unsteady pressure inlet representing a voicing cycle was applied to the sub-glottal region to mimic the time-varying glottal flow.

Intraglottal vortex structures formed downstream of the separation point in a divergent glottis. Their existence caused a higher closing force that was applied onto the vocal folds. A narrow ventricular gap strengthens this effect.

Strength of the intraglottal vortices increased with the maximum flow declination rate. Therefore, a more divergent shape of the glottis during glottal closing will be one of the main contributors to the voice quality.

Keywords

LES; larynx; vocal folds; intraglottal vortices

1. Introduction

According to the classic source-filter theory, the sound is produced at the glottis by flow modulation that results from glottal opening and closing during vibration of the true vocal folds (TVFs). The greatest rate of change in glottal flow occurs during the latter part of the closing phase when velocity rapidly decreases¹⁻³. This rapid deceleration is commonly quantified by the maximum flow declination rate (MFDR)⁴, which has been shown to correlate with acoustic intensity and higher harmonics^{5,6}. An increased MFDR yields a second harmonic that becomes dominant over the first harmonic⁷, which is often associated with more intelligibility⁸.

Some research suggests that one factor that contributes largely to the increase of MFDR is the generation of intraglottal flow separation vortices (FSVs) in a divergent glottis, during its closing. Experiments in a hemilarynx^{9,10} show negative intraglottal gauge pressures, which are hypothesized in our study to be due to vortices. Various types of vortices identified in the laryngeal airflow may condition voice quality, such as those found in the shear layer of the glottal jet, the opening vortex, axis switching vortices, and flow separation vortices. Larger vortices, formed in the supra-glottal region, can affect sound production by interacting with structures located downstream in the vocal tract¹¹. However, these vortices do not significantly impact phonation¹².

Our study focuses on the FSVs located in the glottis. Specifically, these vortices are generated in the superior aspect of the glottis during the closing phase of the vocal folds, when the glottis assumes a divergent shape (i.e., the opening is larger at the superior aspect than at the inferior). As this divergence induces flow separation downstream from the narrower portion of the glottis^{13,14}, vortices develop near the superior aspect of the folds in the separated flow region. These flow separation vortices are hypothesized to contribute to the rapid closing mechanism of the folds by producing negative gauge pressures that generate vocal intensity and prevalence of the high-frequency harmonics in the acoustic spectrum of the produced sound. Other works also suggest that certain laryngeal pathologies (e.g., asymmetric vocal fold tension) will modify both types of vortices and adversely impact sound production^{11,15}. Examination of the pressure field inside the glottis over a full phonation cycle was provided by Sadeghi et. al.¹⁶. Some studies looked at the pressure distribution inside the glottal opening under steady flow¹⁷. Others showed more recently that “*vortical structures may add negative pressure pulses during vocal fold oscillation to augment closing forces within the glottis*”¹⁸. This corroborates experimental measurements conducted in hemi-larynx configurations that showed negative pressures during the closing of the vocal folds in the superior aspect of the glottis (Fig. 1)^{19,20}, where the superior measurement was made in the top 1 mm of the fold and the inferior was made in the bottom 1 mm. Although these measurements were averaged over the size of the pressure transducer (1 mm), a negative inferior-superior pressure gradient was clearly visible. Associated measured velocity fields showed that vortices caused the negative gage pressure²¹. These findings are consistent with the current simplified computational model.

In the current study, a computational model is developed based on the M5 model²² using an unsteady waveform obtained from experiments to simulate the laryngeal flow. Cases

with FSVs are quantitatively compared to cases without them in order to assess the relative contribution of the vortices to the aerodynamic closing force that is applied to the folds. To further the understanding of the laryngeal flow, we developed a computational large-eddy simulation based on the M5 model²² of an unsteady waveform that compared the effects of a straight versus divergent glottal model. Specifically, we quantified the relative contribution of vortices to the aerodynamic closing forces in experiments with and without FSVs. We hypothesized that separation vortices in the divergent section of the TVFs are responsible for a pressure reduction that affects the closing pattern of the TVFs. Clinically this is important because an inferior-superior wave can be absent or small because of unilateral vocal fold paralysis, scarring, or muscle tension dysphonia, and thus affect vocal efficiency²³.

2. Methods

The computational model was constructed based on the geometry of the M5 model²² (Figure 2), and following the same methodology as in²⁴. Four idealized static models (M5) of the human larynx were investigated using large eddy simulation (LES): 2 models with parallel folds did not form flow separation in the glottis and 2 models formed a divergent glottis. Four three-dimensional (3D) static models were created by extracting 2D images in the coronal plane. In each model, the inferior edge of the true vocal folds was set at $x = 0$ mm. The domain then extended from $x = -16.30$ mm in the inferior direction to $x = 52.30$ mm in the superior direction. The subglottal region was 16.30 mm long and the supra glottal region (vocal tract) length was 49.30 mm. The vocal folds height was 3 mm. The resulting computational domain consisted of a square cross-section of 15.24 mm in the sagittal (x-z) and coronal (x-y) directions, and 68.60 mm in the streamwise direction. The minimum glottal width was $w_g = 1.28$ mm.

Of the 4 models, 2 models used 20 degrees divergent angle in the glottis because it corresponded to the closing phase of highest intra-glottal vortex strength²⁵, and 2 models featured straight parallel folds (constant glottal width) in order to eliminate the intraglottal flow separation associated with a divergent duct, thus making possible to isolate the contribution of FSV to the flow. Additionally, vocal tract constriction was varied in both models by changing f , the gap between the FVFs, from narrow ($f=3$ mm) to wide ($f=7$ mm) (Figure 2).

The computational domain was discretized into 1.8×10^6 unstructured hexahedral mesh volumes. Compressible large eddy simulation was employed to quantify laryngeal flow using the commercial solver Fluent, following a methodology that was validated in previous studies using these static M5 models^{24,26}. Flow governing equations on the computational domain were discretized using second-order finite volume schemes. Time integration was performed using an implicit second-order discretization scheme. The semi-implicit method for pressure-linked equation (SIMPLE) algorithm was applied to solve the coupling between the pressure field and velocity field²⁷. The wall-adapting local eddy-viscosity (WALE) model was the subgrid-scale model in this study²⁸. The compressible flow solver provided a complete characterization of the flow field in the vocal tract. No-slip boundary conditions for velocity were set at the solid boundaries of the computational domain. A converged solution based on a steady-state RANS solution with realizable k-epsilon turbulence model

was used to initialize the LES simulations. The time step used in the study was $\Delta t = 2.10^{-5} \text{ s}$. The flow was statistically developed after computing 20 full cycles (4,000 time-steps), and 1 full cycle (220 time steps) was extracted for analysis.

As often in voice-related studies, a quasi-steady assumption was made in the approach of the problem^{29,30}. It assumes that the flow through the glottal orifice can be modeled as static geometries that would match the geometries of the glottis during the opening-closing cycles of phonation. As we are mostly interested in observing the phenomena happening at the beginning of closing, only one static model was designed as described above, and a time-varying pressure waveform was applied at the inlet of the domain, simulating the time-varying conditions due to the opening and closing of the vocal folds. The unsteady flow rate condition for the glottal flow was extracted from experimental data⁶. The transient boundary condition shown in Figure 3 features a peak pressure drop of 14.27 cm of water, which resulted in an averaged pressure inlet of 6 cm of water (sub-glottal pressure level for a normal conversation).

3. Results

Dynamics of the flow were shown at four significant points in the flow cycle (time-stamped t_1 - t_4 in Figure 3) at 45° , 126° , 180° , and 207° as mid-opening phase (maximum positive dP/dt) t_1 , end-opening phase t_2 , beginning of closing phase t_3 , and mid-closing phase (maximum negative dP/dt) t_4 , respectively. For a given sub-glottal pressure, the geometrical configuration of the TVFs/FVFs affected the flow rate. In comparing the streamwise (V_x) velocity profiles at the inferior edge of the TVFs ($x=0\text{mm}$) and superior edge of the folds ($x=2.35\text{mm}$) at the beginning of closing (t_3) (Figure 4), we found that in cases of a narrow gap, peak stream-wise velocities were higher than the similar glottal shape with a wider FVFs gap. At the inferior edge ($x=0\text{ mm}$), stream-wise velocity vectors pointed downstream and the velocity profile was typical of a subsonic convergent nozzle. At the superior edge, left-pointing vectors in the divergent glottis indicated flow reversal. The divergent shape induced flow separation in the glottis that was responsible for the rotational vector field in this area. The magnitude of the reversed vectors was larger for the narrower FVFs gap (top-right graph).

Our results suggest that the shape of the larynx conditioned the glottal flow rate for a given subglottal pressure. The streamwise velocity V_x was integrated across the passage at $x = 2.35\text{mm}$ to calculate the flow rate $Q(t)$. The maximum Reynolds number (calculated at the inferior edge gap at $x = 0\text{mm}$) in the glottis is 15,806 at the peak flow rate.

$$Re = \frac{\rho V_b w_g}{\mu} \quad \text{Equation 1}$$

where ρ is the air density, V_b is the bulk velocity in the rectangular inlet channel, w_g is the minimal glottal gap, and μ is the dynamic viscosity of air.

Results of the integration over a full cycle were compared (Figure 5). In comparing samples, each flow rate was normalized by the flow rate computed for a 3-mm FVF gap with a divergent glottis. Compared with a parallel glottis, the normalized waveforms showed that

the flow rate was always higher in divergent glottis irrespectively of the FVF gap and that the volume flow rate was systematically higher in cases of a narrower FVF gap.

$$Q(t) = \frac{1}{Q_{max}} \int_{y0}^{y1} Vx(t) \cdot dydz \quad \text{Equation 2}$$

3.1. Phase 1: Increase in flow rate

Intraglottal vortices appeared early in the flow cycle but were not resident while the flow was changing. Pressure distribution in the glottis during mid-opening (at t_1) showed positive pressures exerted on the TVFs due to the overall pressure increases in the entire domain and the low velocity (Figure 6). Nevertheless, beyond the separation point, there was already a manifestation of the FSVs with the divergent folds ($0 \text{ mm} < x < 2 \text{ mm}$), which were responsible for the slightly lower pressures on the folds beyond the separation point. These vortices are then convected downstream in the shear of the glottal jet.

3.2. Phase 2: Constant flow rate

FSVs became resident as flow rate stabilized. At t_2 , the inlet pressure was about to reach its maximum value, the flow rate was constant, and the flow was well established in the glottis. In the parallel configurations of the TVFs (Figure 7 a and b), the glottal flow did not separate from the wall, and the pressure was homogeneous in the glottis and supraglottal region. In the divergent glottis (Figure 7c and d), new FSVs formed, which were stronger than the FSVs at t_1 . The negative gauge pressure that resulted from these vortices contributed to decreasing the overall pressure that was applied to the TVFs.

3.3. Mid-Closing Phase

The maximum effect of the FSVs was featured when the flow started to decrease, which can be assimilated to the beginning of the closing TVFs. The 20° divergent geometry of the glottis studied here corresponded to the middle of the closing phase (t_4). At this point, the FSVs formed in the glottis remain localized (i.e., did not convect downstream), and the flow rate was decreasing at its highest rate. In comparing the pressure contours of the 4 cases at this phase, pressure distribution on the straight folds (Figure 8a and b) was homogeneous, had relatively low negative values (with respect to atmospheric), and showed no significant effect of the various gaps between the FVFs. However, the pressure distribution on the divergent folds (Figure 8c and d) was quite different, was dominated by the FSVs within the glottis, and showed significantly lower pressure levels (compared with straight folds), particularly near the FSVs.

The FSVs were larger and more pronounced with the narrower FVFs and therefore the pressure distribution was lower for in these cases. These quantitative differences are shown by the plots of the pressure distribution along the folds (Figure 8e and f).

3.4. Forces

The maximum closing forces corresponded to the initiation of the MFDR in the glottal cycle. The aerodynamic forces applied to the glottal wall were computed by integrating the pressure along the straight portion of the TVFs, namely for $0 \text{ mm} < x < 2.5 \text{ mm}$ in each case, as defined by Equation.

$$F(\varphi) = \int_{x=0\text{mm}}^{x=2.5\text{mm}} P(x, \varphi) \cdot dx \quad \text{Equation 3}$$

A 4th order Fourier series was fitted to the results of this integration for each case and plotted in Fig. 8. The choice of the fit only depended on the visual aspect of the resulting curve and the actual benefit in appreciating the trends. The equation of the fit is as below:

$$F(\theta) = a_0 + \sum_{i=1}^4 (a_i \cos i\omega\theta + b_i \sin i\omega\theta) \quad \text{Equation 4}$$

where ω is the fundamental frequency of the signal, 4 is the number of terms (harmonics) in the series, and $F(\theta)$ is the force applied to the folds as a function of the phase (θ). The forces were normalized by the maximum value obtained with divergent folds and narrow FVFs gap (3 mm). The divergent geometry with the narrower FVFs gap (3 mm) experienced a greater negative force when the flow was decelerating ($dQ/dt < 0$) than all other cases, including the case of the divergent model with the wider FVFs gap (7 mm). This directly correlated to the presence of strong FSV in the glottis during the closing phase. The force attained its maximum value in the beginning of closing ($\varphi \sim 170^\circ$) and approached the level of the others on completion of closing ($\varphi \sim 270^\circ$).

Figure 10 compares the values of the integral of the force (P_F), over the simulated closing phase of the cycle ($170^\circ < \varphi < 270^\circ$), in the form of a bar graph. The expression for P_F is defined by Equation.

$$P_F = \frac{1}{P_{F_{\max}}} \int_{\varphi=170^\circ}^{\varphi=230^\circ} F(\varphi) \cdot d\varphi \quad \text{Equation 5}$$

These integrals were normalized by the maximum value $P_{F_{\max}}$ for comparison. The two shorter bars correspond to the case of parallel folds in which separation did not occur in the glottis, thus allowing only Bernoulli's pressures to determine the negative forces applied to the folds. The two longer bars represent the forces with FSVs for both narrow and wider FVF gaps. Closing forces increased 136% with the narrow FVF gap and 157% with the wider gap.

4. Discussion

4.1. Overview

As hypotheses evolve related to the impact of flow separation and formation of separation vortices during the closing phases of a glottal cycle, our computational study provides a quantitative understanding of unsteady waveform toward the eventual goal of clinical

applications. In comparing the effects of a straight versus divergent glottal model, we identified the relative contribution of vortices to the aerodynamic closing forces. Our hypothesis is that separation vortices in the divergent section of the TVFs proved responsible for a pressure reduction of more than 136% in the closing pattern of the TVFs.

4.2. Straight vs. divergent glottis

Our findings suggested that a divergent glottis during closing will display higher skewness in the glottal flow waveform than a straight glottis. Past research that described glottal flow most often used a Bernoulli approach^{22,31–33}, which simplified the highly complex flow phenomena associated with phonation, including those caused by turbulence and vortices. However, recent papers assumed that the Bernoulli was inadequate downstream to the separation point and that pressure was zero downstream. Experiments in a hemilarynx^{9,10} showed negative gauge pressures, which were hypothesized in this model to be due to vortices. Bernoulli's effect alone does not suffice to explain the lower pressures in the divergent case. If flow separation does not occur, one would expect the divergent shape of the glottis to induce an increase in pressure due to the pressure recovery that happens in the diffuser-like divergent glottis.

Several experimental^{6,15,22} and computational studies^{34–36} have shown that vortices can form near the superior aspect of the glottis during the closing phase of the vibration of the folds. This was characterized by a higher strength of transverse vorticity in the flow and negative gauge pressure on the surface of the TVFs. Different approaches aimed at quantifying the forces that these vortices induce on the folds have been proposed^{35–37}.

Others have also shown that they generate a negative gauge pressure on the false vocal folds. Whether or not they significantly impact the folds' vibrations depend on their relative contribution to the pressure distribution on the vocal folds. In our study tackling the question of this relative contribution, we showed that a divergent glottis will allow for separation at the inferior aspect of the folds, which is the origin of the vortices that correlate directly with the stronger closing force applied on the TVFs.

4.3. Narrow vs. wide FVFs gap

Our findings confirm the influence of the inertance on the skewing of the glottal waveform, showing that it does not cause it but rather it strengthens it. This corroborates past findings using different numerical methods to study the effects of FVFs on the glottal flow³⁸. Indeed, some have postulated that vocal tract inertance is at the origin of the negative gauge pressure^{39,40}. Farbos de Luzan et al. used the M5 model of Scherer et al. with a steady velocity inlet to show that a narrower gap between the FVFs increased the circulation of the FSVs in the divergent part of the glottis, resulting in a stronger induced closing force on the TVFs, and contributed to a faster closing of the folds. Although the intensity of the forces applied to the TVFs increased with the inertance of the vocal tract, the most substantial consequence of narrowing the FVFs gap was a straighter glottal jet. Similarly, Xue and Zheng (2016) showed in a numerical study an increased flow rate with a reduced supra-glottal gap (by addition of a vocal tract). Subsequently, the jet velocity increased as it traveled through this straight narrow channel, and the intraglottal negative gauge pressure was conditioned by

the jet velocity within the glottis. Although intraglottal vortical activity was strengthened by entrainment, more important was the negative gauge pressure that it generated. In the presence of the FSV, pressure decreased significantly with a narrow FVF gap and only slightly decreased with a wide FVF gap. Consequently, the force that applied to the TVFs was stronger and helped to close them faster.

4.4. Study limitations

This study voluntarily limited itself to studying the benefit of having a diverging glottis during the closing of the glottal cycle. Thus, static models were used. This contrasts with the person's changing glottal geometry from a convergent to a divergent shape that is characteristic during phonation. Such a limitation can be overcome by employing a more complex flow-structure-interaction (FSI) modeling. The quasi-steady assumption is also limiting as it does not consider the full dynamics of the moving tissue during phonation. A flow structure interaction (FSI) model is considered for the future development of this study, such as the model developed by Luo et al.^{38,42}.

5. Conclusion

Our computational study investigated the impact of flow separation and the resultant separation vortices on the closing forces during the closing phase of a glottal cycle. Toward this aim, our model quantified the intraglottal pressure distributions and the forces exerted on the folds by comparing 2 models, one representing the geometry of divergent folds during closing and a second of parallel-fold geometry that prevented the formation of FSV. Our findings showed the FSVs contributed substantially to the intraglottal negative gauge pressure and the closing force that it exerts on the vocal folds during MFDR. Moreover, our large eddy model of the glottis (parallel vs. divergent) enabled isolation of the contribution of the FSVs to the aerodynamic effects in the glottis during the negative dQ/dt phase of the flow cycle or the closing phase of the folds. A divergent glottis, combined with a narrow FVFs gap, set an optimal configuration for a strong intraglottal vortical activity. That is, the faster closing of the divergent glottis increased the skewing of the glottal waveform, which is related to the generation of higher harmonics and better voice quality. Thus, our findings help to further establish the direct link between the FSVs existence and improved quality of voice.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1:
(reproduced from Oren et. al.²⁰) Pressure measurements in the superior and inferior aspect (showing mean waveforms) in an excised canine hemilarynx, at subglottal pressure PSG = 26.6 cm H₂O. Solid line is showing best fit to the data. Dashed line is showing data reproduced from Alipour and Scherer⁴³.

Figure 2:

(Color online) Computational flow domain. Overlay depicts the 4 geometric sections of the 4 models obtained by combining the TVFs configurations (straight or divergent) and FVFs configurations (3- or 7-mm gap). Computational domains resulted from an extrusion of the sections along the z-axis ($dz=15.24\text{mm}$). Difference between the geometries: dark gray represents regions of the flow domain in the transition from parallel/straight TVFs to divergent FVFs gap. Dashed red-lined rectangle delineates the focus region of the analysis (detail will be magnified in the next figures).

Figure 3:

(Color online) Inlet pressure boundary. Computation setup uses a previously reported glottal flow cycle (Oren et al., 2015b). The normalized dP/dt is overlaid to show the locations of t_1 - t_4 , for which flow details will be shown later. The period of the chosen signal resulted in a simulated glottal cycle of ~ 200 Hz. The derivative of the pressure waveform (dashed line) helps to locate MFDR (t_4). Outlet boundary condition assumes uniform atmospheric pressure.

Figure 4:

(Color online) Vectors of streamwise velocity (V_x) along with profiles located at the inlet and the outlet of the glottis, at $\phi = 180$ degrees (peak computed flow rate), which corresponds to the time-stamp t3. The two figures on top correspond to the cases featuring a narrow FVFs gap (3mm), while the bottom ones feature a wide FVFs gap (7mm).

Figure 5:

(Color online) Flow rate through the glottis during the full cycle. The sub-glottal pressure (noted PSG) is overlaid for reference and shows how the flow is maximal right before the sudden drop in PSG. Divergent glottis and vocal inertance increase the flow rate.

Figure 6:

(Color online) Detail of the flow at t_1 ($\phi = 45^\circ$). a) straight / narrow gap; b) straight / wide gap; c) divergent / narrow gap; d) divergent / wide gap; and e) and f) corresponding pressure profiles along the folds. The contours plots show the pressure distribution in the glottis during mid-opening (at t_1). The pressure exerted on the TVFs is positive (shown as red shade contour) due to the overall rise of the pressure in the entire domain.

Figure 7:

(Color online) Detail of the flow at t_2 ($\phi = 126^\circ$). a) straight / narrow gap; b) straight / wide gap; c) divergent / narrow gap; d) divergent / wide gap; and e) and f) corresponding pressure profiles along the folds. FSVs are increasingly stagnating in the divergent region of the true vocal folds (TVFs) and the induced pressure difference is more established. The contour plots show darker areas in the vicinity of the vortices, and gradient of pressure in between them. This is the moment in the cycle where the vortices stop shedding downstream and start localizing to the glottal region, until t_4 .

Figure 8:

(Color online) Detail of the flow at t_4 ($\phi = 207^\circ$). a) straight / narrow gap; b) straight / wide gap; c) divergent / narrow gap; d) divergent / wide gap; and e) and f) corresponding pressure profiles along the folds. Flow is starting to decrease, and vortices are at their maximum strength. The pressure exerted onto the TVFs is maximal.

Figure 9:

(Color online) Forces exerted on the TVFs over a full flow cycle. Curves fitted onto the data points depict the trends: that is, the narrower the FVFs gap, the stronger the negative force. The same trend followed between the parallel and divergent glottis.

Figure 10:
 (Color online) Average force resulting from the pressure applied onto the TVFs during the simulated closure of the folds. Quantification of the observed trends confirms the hypothesis, thus distinguishing the effects of FSVs from those of Bernoulli alone.