5pSC1. Quantification of the false vocal-folds effects on the intra-glottal pressures using large eddy simulation

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During the closing phase of the phonation cycle the true vocal-folds (TVF) have a convergent-divergent shape. The negative pressures generated by the flow through the glottal passage are producing closing forces acting on the TVFs. They can affect both vocal-fold vibration and voice production, since they can accelerate the closing phase. Large Eddy Simulation approach is used to investigate the intra-glottal forces generated solely by the flow during the closing phase. The influence of the gap between the false vocal-folds (FVFs) and the location of FVFs with respect to the TVFs are analyzed. Based on anatomical measurements, four different widths between the FVFs and two different distances between the true and false vocal-folds are investigated for the same trans-laryngeal pressure. The TVFs gap is kept constant. All cases exhibit a non-symmetric flow behavior in the mid-frontal plane. As the distance between the FVFs is decrease beyond a threshold value (still greater than glottal width), there is an increase in the magnitude of the closing forces acting on the TVFs. On the divergent slope of the glottis, these forces were found for some of the cases to be up to four times greater in magnitude as compared with the Baseline case.

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INTRODUCTION

The use of Computational Fluid Dynamics (CFD) in investigating the non-linear glottal airflow has been facilitated by advances in computer technology over the last few decades. Within this context, Large Eddy Simulation (LES) has become the major computational tool for studying such unsteady transitional/turbulent flows. LES resolves a large range of turbulent scales (i.e. the energy containing eddies) and thus is able to capture the dynamics occurring in the flow (Pope, 2000). Only the smallest scales in the turbulent flow need to be approximated by modeling. More robust CFD formulations, such steady-state Reynolds Averaged Navier-Stokes (RANS) with two-equation turbulence models (e.g. k-ε or k-ω) cannot describe accurately unsteady flow fields involving flow separation and adverse pressure gradients (Wilcox, 1993). With such models only information about the local mean flow is computed. For some flow situations characterized by adverse pressure gradients and separation, unsteady RANS based on shear-stress transport (SST) k-ω model may be a better choice as compared to other RANS models since it offers a better trade-off between accuracy and efficiency (Suh and Frankel, 2008).

Unsteady CFD calculations were performed for various glottal configurations (2D, axisymmetric, 3D) with or without including vocal folds motion (Zhao, Frankel, and Mongeau, 2001; Zhang et al., 2002; Hofmans et al., 2003; Alipour and Scherer, 2004; Decker and Thomson, 2005; Mihaescu et al., 2007; Suh and Frankel, 2007). The sound associated with the laryngeal airflow was considered in some of the models (Zhao, Frankel, and Mongeau, 2001; Zhang et al., 2002; Mihaescu et al., 2007; Suh and Frankel, 2007). Parametric studies involving the Reynolds number influence on the flow characteristics and the effect of different divergent glottal angles on the flow separation point were performed (Zhang et al., 2002; Alipour and Scherer, 2004; Mihaescu et al., 2007). It is known that for a diverging shape of the vocal folds, when the angle of the glottis exceeds a certain minimal value, the flow separates and vortices are formed immediately downstream of the separation point (Zhao, Frankel, and Mongeau, 2001; Zhang et al., 2002; Mihaescu et al. 2010). In most of the cases, despite of the symmetric glottal models used, the flow was found to lose its symmetry (e.g. Scherer et al., 2001; Erath and Plesniak, 2010). Several studies, mostly experimental (Miller et al., 1988; Pelorson et al., 1994; Agarwal, 2004; Kucinschi et al., 2006; Bailly et al., 2008), considered the false vocal folds (FVF) effects on the glottal airflow. The separated glottal jet from the true vocal folds (TVF) was found to be straightened by the presence of the ventricular folds. For certain configurations the presence of the FVF caused an enhancement of low pressures (i.e. more negative pressures) in the glottis.

In the present research, LES is used to investigate the intra-glottal forces generated solely by the flow during the closing phase of the phonation cycle. The closing phase has an important effect on the voice quality; rapid closing correlating well with the voice intensity and loudness (Sundberg and Gauffin, 1979; Woo, 1996; Stevens, 1998). How the gap between the FVFs and the location of FVFs with respect to the TVFs are changing the intra-glottal pressures and the pressure forces acting on the folds is analyzed.

MODELS AND METHODS

Within the framework of the CFD software package Fluent 13.0 (ANSYS®, USA) the LES approach is selected for capturing the dynamics associated with the laryngeal airflow in several configurations without and with ventricular folds. A total of nine laryngeal models are considered including the Baseline case (i.e. without the FVFs). All the cases are summarized in Table 1 and sketched in Fig. 1. Four different gaps between the FVFs (WgFVF) and two different distances (L) between the true and false vocal-folds (based on anatomical measurements) are analyzed for the same trans-laryngeal pressure of 7 cmH2O. The distance between the TVF (i.e. glottal gap WgTVF) is kept constant for all the simulations.

Figure 1 depicts the main geometrical features of the investigated glottal configurations. The TVFs are described through a convergent-divergent shape, characteristic to the closing phase of the phonation cycle. Thus, a 40 degrees divergent glottis (2 x 20 degrees angle for the TVF) is considered. For the FVFs a 60 degrees divergent angle (2 x 30 degrees angle) is simulated. The shape and dimensions for the vocal folds are according to Agarwal (2004). The effect of vocal folds movement on the flow is not considered. All the computational domains are defined by a square cross-section of 15.24mm by15.24mm and by a length of 60mm in the stream-wise flow direction (z).

The grid quality is important for an efficient and an accurate flow simulation. Unstructured hexahedral body fitted meshes with about 1.5x10^6 computational mesh volumes are used to discretize each of the computational domains corresponding to the cases presented in Table 1. Detailed LES flow calculations in the near-wall region (i.e. near the vocal folds) are possible due to the high grid resolution used in this region (see Fig. 1d). All the
computational grids are smoothly stretched in the wall normal direction to assure a $y^+$ dimensionless distance near the wall of the order of one.

**TABLE 1.** Summary of the set-ups and geometrical features characterizing the investigated laryngeal models.

<table>
<thead>
<tr>
<th>Case notation</th>
<th>Glottal gap, $W_{gTVF}[\text{mm}]$</th>
<th>Ventricular folds gap, $W_{gPVF}[\text{mm}]$</th>
<th>Distance between the TVF and FVF, $L[\text{mm}]$</th>
<th>Trans-laryngeal pressure, $\Delta p \ [\text{cmH}_2\text{O}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1.6</td>
<td>N/A</td>
<td>N/A</td>
<td>7 ($\sim 690 \text{ Pa}$)</td>
</tr>
<tr>
<td>C1</td>
<td>1.6</td>
<td>8.58</td>
<td>2.67</td>
<td>7</td>
</tr>
<tr>
<td>C2</td>
<td>1.6</td>
<td>6.23</td>
<td>2.67</td>
<td>7</td>
</tr>
<tr>
<td>C3</td>
<td>1.6</td>
<td>4.50</td>
<td>2.67</td>
<td>7</td>
</tr>
<tr>
<td>C4</td>
<td>1.6</td>
<td>3.00</td>
<td>2.67</td>
<td>7</td>
</tr>
<tr>
<td>F1</td>
<td>1.6</td>
<td>8.58</td>
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<td>F2</td>
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</tr>
<tr>
<td>F4</td>
<td>1.6</td>
<td>3.00</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

**FIGURE 1.** Computational domains within the context of the present study: (a) the Baseline configuration, (b) C1 to C4 configurations; (c) F1 to F4 configurations; (d) detail of the generated mesh close to the surface of the divergent glottis.

The very low Mach number airflow allowed assuming flow incompressibility. The flow governing equations are discretized on the computational grids using second-order finite-volume schemes. For the time integration, a second-order implicit scheme is employed. The coupling between the velocity and pressure fields is realized using the Semi-Implicit Method for Pressure-Linked Equations corrected algorithm (SIMPLEC) with improved convergence as compared to SIMPLE. The Wall-Adapting Local Eddy-Viscosity (WALE) Subgrid-Scale model designed to return the correct wall asymptotic behavior for wall bounded flows is used. The trans-laryngeal pressure is kept constant during the simulations; pressure inlet and pressure outlet boundary conditions are imposed to cause the desired trans-laryngeal pressure drop of 7cmH$_2$O. No-slip boundary condition for velocity is imposed at the walls of the computational domain. The time step used with the present LES calculations is of $2\times10^{-5}$ sec. The simulations were performed for approximately 40 flow-through times, achieving a converged solution at each time-step. All the LES calculations are initiated from converged steady-state RANS flow data obtained using the $k$-$\varepsilon$ turbulence model. The described LES solver was previously validated for cases relevant to biofluid dynamics (Mylavarapu et al., 2009; Mihaescu et al., 2011).

**RESULTS AND DISCUSSIONS**

The time-averaged axial velocities as calculated from the LES data for all the nine cases are presented in Fig. 2. Flow streamlines are over-imposed on the velocity fields. All the cases exhibit a non-symmetric flow behavior in the mid-frontal plane, with the glottal jet attaching to one side or the other of the wall. The asymmetry is due to the fact that the flow at higher Reynolds numbers (turbulent flow) is unstable and undergoes several states of bifurcations (e.g. Fuchs, 1989; Drikakis, 1997). The bifurcations are highly dependent on the geometry (i.e. nozzle to downstream diameter ratio). Due to bifurcation any small perturbation leads to a selection of a non-symmetric mode. The asymmetry of the mean velocity field is maintained by the so called Coanda effect; i.e. once the glottal jet attaches to the wall, it remains attached. Which of the two possible asymmetric solutions is computed depends on
the perturbations in the system. The perturbations caused by the numerical scheme (for example the direction of relation) may be enough to trigger and select one of the asymmetric solutions.

**FIGURE 2.** Time-averaged axial velocities (m/sec) as calculated by LES in the mid-frontal plane of the laryngeal models presented in Table 1: Baseline and C1 to C4 configurations on the left; F1 to F4 configurations on the right.

**FIGURE 3.** Comparisons of time-averaged axial velocity data (m/sec), plotted along lines located in the mid-frontal plane as indicated in the top row figures: (a) C1, C2, C3, C4 configurations; (b) F1, F2, F3, F4 cases. See Table 1 for case description.

Figure 3 presents a more quantitative comparison between the investigated configurations in terms of time-averaged axial velocities. The data are extracted along cross-lines located at several positions in the y-z mid-plane of the models as depicted in Fig. 3 (top-row). As the gap between the FVFs is closing, the glottal jet gets straighter and higher peak velocities are found within the glottal jet. These effects are enhanced for the cases in which the FVF are
located at a greater distance from the TVF (F1 to F4). Within all the cases the peak velocities are the greatest for the F3 and F4 configurations. One can remark also the larger rotational structures formed in the laryngeal’s ventricle for the F1 to F4 cases as compared to C1 to C4 configurations (see Fig. 2).

![Figure 4](image1.png)  
(a) RMS of static pressures (Pascal), plotted along lines located in the mid-frontal plane as indicated in the top row figures: (a) C1, C2, C3, C4 configurations; (b) F1, F2, F3, F4 cases. See Table 1 for case description.

The fluctuations in the static pressure data at the wall’s surface are an indication of the regions where the acoustic sources due to the unsteady pressure loads on the surface of the glottal walls (the dipole acoustic sources) are important. Figures 4a and 4b expose the root-mean-square (RMS) values of static pressure data as calculated by LES for C1 - C4 and F1 - F4 configurations, respectively. The plots are along the same lines as used before for quantifying the velocity fields (see top-row in Figs. 3 and 4). In general, as closing the FVF, the magnitude of the wall pressure fluctuations increases in the region of the TVFs (divergent slope) and ventricle space (lines 2 and 3 in Fig. 4). However, it is interesting to note that for the C3 and C4 set-ups (L = 2.67mm, Fig. 4a) the data within this region are converging towards about the same value of 55 Pa, despite of the decrease in the FVFs gap ($W_{FVF}$) from 4.5mm to 3.0mm.

As decreasing the gap between the FVF for the “F” laryngeal configurations ($L = 6mm$), the fluctuating wall static pressures in the region of the TVFs (divergent slope) and ventricle space (lines 2 and 3 in Fig. 4) tend to converge towards the same value but starting at even larger FVF widths (i.e. F2 model, $W_{FVF} = 6.23mm$). Thus, theoretically for similar glottal widths, by increasing the ventricle space (i.e. increasing L from 2.67mm to 6mm) is possible to elevate the static pressure RMS values on the TVF and thus to enhance the surface acoustic sources due to unsteady pressure loads.

![Figure 5](image2.png)  
FIGURE 5. Normalized flow resistances with respect to the Baseline case (without the FVF) as calculated for C1 to C4 and F1 to F4 cases.
The flow resistances were calculated for each case in part based on the imposed trans-laryngeal pressure drop of 7cmH2O and the calculated time-averaged flow rate ($\Delta p/\Phi$). The normalized flow resistances with respect to the Baseline case (without FVF effect) are presented in Fig. 5 as a function of the normalized glottal gap ($W_{g/FVF}/W_{g/TVF}$). The data agrees in qualitative terms with the observations made experimentally by Agarwal (2004) or Bailly et al. (2008); i.e. as the gap between the FVF is decreasing there is a certain threshold value ($W_{g/FVF}/W_{g/TVF} < 4$) after which the resistance of the glottal model with FVF becomes lower than that of the Baseline case. Naturally, an increase of the trans-laryngeal resistance of the models with FVF above the Baseline case is expected once the FVF’s width becomes smaller than the distance between the TVF (i.e. $W_{g/FVF}/W_{g/TVF} < 1$) (e.g. Agarwal, 2004; Bailly et al., 2008).

Increasing the distance between the FVFs and the TVF from 2.67mm to 6mm enhances the effect described in the previous paragraph, as it is shown also in Fig. 5. The data calculated for the F3 and F4 laryngeal models ($L = 6mm$) indicate an important reduction in laryngeal resistance as compared with the Baseline and as compared with the C laryngeal models ($L = 2.67mm$).

(a) 
(b) 
**FIGURE 6.** Definition of the minimum cross-sectional area region (a) and of the divergent slope region (b) as discussed within the “Results and Discussions” section.

The pressure forces on the TVF are largely affected by the location of the FVF. Figure 7 presents the mean static pressures as calculated for all the configurations (including the Baseline) on the surface of the TVFs as a function of the normalized glottal gap ($W_{g/FVF}/W_{g/TVF}$). In a previous study of a convergent-divergent glottal model, it has been shown that intra-glottal vortices are formed on the divergent wall of the glottis, immediately downstream of the separation point (Mihaescu et al., 2010). These vortices are intermittently shed near-by the divergent slope of the glottis, producing unsteady flow at the glottal exit. The vortical structures are characterized by significant negative static pressure relative to the ambient pressure. In order to better quantify this effect, the TVF’s surface was divided into the minimum cross-sectional area region (MCSA) and the divergent slope region as depicted in Fig. 6. Moreover, the pressure data in Fig. 7 were calculated on both the “flow-side” (i.e. glottal flow attaches to that side) and the “no-flow side”.

(a) 
(b) 
**FIGURE 7.** Area-weighted averaged static pressures (Pa) as calculated for all the configurations on both “flow” (a) and “no-flow” (b) sides of the glottis, respectively. See Fig.5 for the definition of MCSA and of the divergent slope region.

It is reminded that the glottal jets are straighter for the C4 set-up as compared with the other “C” configurations and even straighter for the F3 and F4 models as compared with all the other (see Figs. 2 and 3). The calculated trans-glottal resistances are lower due to the higher glottal flow rates encountered for the same trans-laryngeal pressure (see Fig. 5). Larger peak airflow velocities were calculated for these configurations near-by the glottal walls as it was already shown in Fig. 3. As a result, more negative pressures (larger closing forces on the TVFs) were
calculated for the F3 and F4 configurations as compared with all the other set-ups (Fig. 7). Despite of some quantitative differences, the resemblance between the “flow” and the “no-flow” sides is obvious.

![Figure 8](image)

**FIGURE 8.** Pressure forces (N) on the surface of the glottis as calculated for all the configurations on both “flow” (a) and “no-flow” (b) sides, respectively. See Fig.5 for the definition of MCSA and of the divergent slope region.

The pressure forces acting on the TVF surfaces solely due to the flow are presented in Fig. 8. As the distance between the FVF’s is decrease beyond the threshold value of \( \frac{W_{g_{FF}}}{W_{g_{TF}}} < 4 \), there is an increase in the magnitude of the forces acting on the TVFs. The closing forces acting on the divergent slope of the glottis calculated for the F4 set-up were found to be about three to four times greater in magnitude as compared with the Baseline case. These negative pressure forces in the wider, superior aspect of the glottis are consistent with the location of the intra-glottal separated structures previously observed in numerical laryngeal models (Zhao, Frankel, and Mongeau, 2001; Zhang et al., 2002; Mihaescu et al. 2010) or in excised canine larynges (Khosla et al. 2009). They work in the direction of accelerating the closing phase of the phonation cycle relative to the opening phase and possible improve the voice quality.

**SUMMARY**

Large Eddy Simulations of the incompressible airflow through eight laryngeal models with FVF and one laryngeal model without FVF effects were performed. The closing phase of the phonation cycle for which the TVF have a convergent-divergent shape was investigated. The gap between the FVF’s and the location of FVF’s with respect to the TVFs are the parameters in the study. Their influence on the laryngeal flow and on the generated intra-glottal pressures is analyzed. It should be noted that the changes in the geometry were chosen in accordance with anatomical data (Agarwal, 2004).

Despite of the symmetric geometries of the models, asymmetric flow fields developed downstream of the flow separation point on the divergent 20 degrees glottis. As the gap between the TVF is closing the intra-glottal flow gets straighter. The highest curvature for the intra-glottal jet was found for the Baseline case, while the lowest was found for the case with the narrowest width between the FVF’s. The effect is enhanced for the cases in which the FVFs are located further downstream from the TVFs \((L = 6\, mm)\).

For normalized FVF glottal gaps of \( \frac{W_{g_{FF}}}{W_{g_{TF}}} > 4 \) the pressure forces are predicted more or less constant and roughly equal to the data obtained for the Baseline configuration. If the gap between the FVF’s is decreased so that \( \frac{W_{g_{FF}}}{W_{g_{TF}}} < 4 \) the closing pressure forces acting on the TVFs are becoming more important.

The pressure forces on the TVF are largely affected also by the location of the FVF as reference to the TVFs. Larger closing forces on the TVF’s (more negative pressures) were calculated for the cases in which the TVF are at a greater distance downstream from the TVFs and for which the normalized glottal gap is \( \frac{W_{g_{FF}}}{W_{g_{TF}}} < 4 \). Since the laryngeal jet is straighter in these cases, the calculated trans-glottal resistances were lower resulting in higher flow rates for the same trans-laryngeal pressures, and hence higher glottal jet velocities, which are causing lower pressures on the TVFs. Nevertheless, the trans-laryngeal resistance of the models with FVF’s is expected to increase significantly as the FVF’s gap is decreasing bellow the glottal width (i.e. \( \frac{W_{g_{FF}}}{W_{g_{TF}}} \leq 1 \)) fact shown by several authors (e.g. Agarwal, 2004; Bailly et al. 2008).
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