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INFLUENCE OF SUPRAGLOTTAL TRACT ON FLOW SEPARATION VORTICES DURING VOCAL FOLD CLOSING IN HUMAN PHONATION

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Keywords: Flow Separation Vortices; Supraglottal Tract; Intraglottal Negative Pressure

Abstract:

Objectives / Introduction:

The oscillation of the vocal folds results from the interplay between glottal aerodynamics and tissue elasticity. In this process, intraglottal pressure serves as the driving force. This pressure during the closing phase of the fold vibrations is particularly interesting because of the vortical structures that can form by flow separation and impact the glottal dynamics [1,2]. Our previous study [3] showed through computational models that the mean negative pressure during glottal closing can be about 28% of the subglottal pressure. In the comparative cases where the negative intraglottal pressures were artificially removed, the vibration amplitude and flow rate were reduced by up to 20%, and the closing speed, flow skewness quotient, and maximum flow declination rate were reduced by up to 40%.

The main limitation of our previous study [3] was excluding a supraglottal tract from the model. Natural human phonation involves a supraglottal tract, and its presence affects the intraglottal pressure through flow inertia. In the current study, we aim to analyze the impact of the supraglottal tract on negative intraglottal pressures during glottal closing. We propose to examine two interactive mechanisms contributing to the negative intraglottal pressure formed during closing: (1) from the flow separation that forms in a divergent glottal shape and (2) from flow inertia in the supraglottal tract.

Methods:

Numerical simulation of glottal flow aerodynamics is conducted using a hydrodynamic/acoustic splitting method [4], which has been validated [5] and used in our previous work [3]. The simulation employs the three-mass model wherein the body-cover structure of the vocal fold is represented by three lumped masses connected through springs and dampers [6]. In the fluid-structure interaction (FSI) simulation, the displacement and velocity of the upper and lower masses from the three-mass model are provided to the flow model to update the flow field; additionally, the surface pressure from the flow model is utilized to calculate the external force on the three-mass model, therefore, driving its motion.

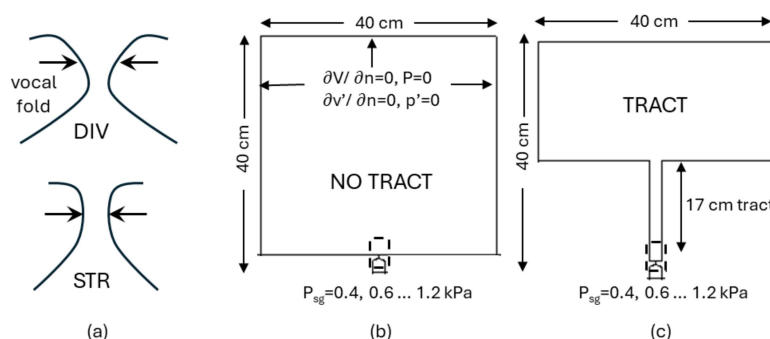


Figure 1. Simulation setup. (a) In the DIV (divergent) group, the glottis forms a divergent shape during closing. In the STR (straight) group, the glottis forms a straight channel during closing. These differences in glottal behavior are achieved by adjusting the parameters of the three-mass vocal fold model. (b) The open-space flow domain setup for NO TRACT condition. The glottis directly opens to a large open space (c) The flow domain setup for TRACT condition. The glottis is connected to a supraglottal tract, which opens to a large open space.

Four groups of simulations were conducted (Figure 1). In the DIV (divergent) groups, the three-mass parameters are consistent with those used in [3]. These parameters generate a divergent glottal shape during closing. The glottis is connected to an open space or supraglottal tract, representing the conditions without-tract (NO TRACT DIV) and withtract (TRACT DIV). In the STR (straight) groups, we adjusted the parameters of the three-mass model to achieve a

nearly straight channel shape during vocal fold closing in both without-tract (NO TRACT STR) and with-tract (TRACT STR) conditions. The open space and supraglottal tract geometries are identical for the DIV and STR groups. In each group, the subglottal pressure ranges from 0.4kPa to 1.2kPa with increments of 0.2kPa.

Results:

Sustained vibration was achieved in all cases. Figure 2 shows the minimum glottal angle, the peak glottal flow rate, and the mean pressure on the vocal fold medial surface during closing. The minimum glottal angle during vocal fold closing in the STR group is close to zero but can be slightly divergent. The peak flow rate was not affected by the tract but was higher when the vocal folds closed in a straight rather than divergent glottis shape.

Regarding the mean pressure during glottal closing, due to the minimal flow separation in STR cases, we propose that the effect of the supraglottal tract in the STR conditions is primarily due to flow inertia in the tract, while the impact of the supraglottal tract in the DIV conditions is due to the combined effects of flow inertia in tract and flow separation in the glottis. It is observed from Figure 2 that the presence of the supraglottal tract largely reduced intraglottal pressures in DIV cases. In contrast, this effect is much smaller or even the opposite in STR cases. Furthermore, it is noticed that the mean pressure difference is smaller between DIV and STR groups when no tract is present (No TRACT STR vs NO TRACT DIV in Figure 2), suggesting a smaller effect of flow separation on the pressures without a tract. These results suggest that the presence of the supraglottal tract can further reduce the negative intraglottal pressure during glottis closing by affecting flow separation-induced negative pressures, potentially by strengthening the intraglottal vortices. However, this hypothesis needs to be further examined.

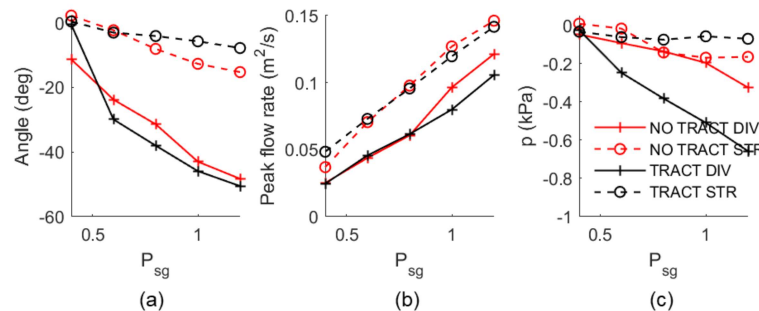


Figure 2. (a) Minimum glottal angle. (b) Peak glottal flow rate. (c) Mean pressure of the medial surface during vocal fold closing.

Conclusions:

During normal human phonation, the intraglottal negative pressure is affected by both the inertance of the supraglottal tract during flow declination and the flow separation in a divergent glottis. To quantify the impact of the supraglottal tract, we conducted two groups of simulations where the vocal folds closed either straightly or divergently, with and without a supraglottal tract. The results indicate that, in addition to directly reducing intraglottal pressure through the flow inertia in the tract, the supraglottal tract may also indirectly lower intraglottal pressure by reinforcing the negative pressure generated by flow separation.

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