SIMULATION OF THE THREE-DIMENSIONAL FLOW IN THE HUMAN LARYNX

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1.   INTRODUCTION

Human phonation has been studied using various methods since Flanagan's two mass model [1]. Titze [2], Alipour [3], and Scherer[4] have produced studies ranging from ex-vitro experiments using excised canine larynxes, duct type Plexiglas steady flow, and dynamic models and many using computational simulation and finite element methods. The role of the vocal fold is well explained and the fundamental frequency relatively well documented. Work has mostly been centered on the glottis, and other parts of the human larynx have only been the topic of a few studies. Three-dimensional analysis of airflow has only been a topic recently included in a few relatively recent works [5-6]. Open questions lie in explaining the hysteresis between the onset and offset threshold pressures in phonation [7], and the nature of the effect of the ventricular fold and supraglottis on the airflow—particularly on the separation point. This project is intended to build on these experiments in order to provide more details about these open questions.

2.   METHOD

The three dimensional model was constructed as to represent realistic structures from the trachea up to the epiglottis. The model was designed using approximations based on a collection of average male values taken from morphometric studies. The subglottic and supraglottic zones were constructed based on morphometric measurements taken from [8] and [9]. The ventricular folds data is coming from laminographic tracings extracted from [4 and 10]. The lungs are treated as a constant pressure source. The flow assumed to be at steady state. Although some experiments do caution about using the quasi-steady assumption, as discussed in [11], it was considered appropriate for the current simulation. It is justified by the fact that the simulation is mostly intended as a qualitative investigation of the flow characteristics around the ventricular folds and that the model complexity is already inflicting a high computational cost.

The model geometry was also inspired from a collection of histological cuts of the human larynx in an attempt to mimic the variation in cross section of the ventricular folds. This tissue fold encloses the ventricular ligament that is attached on the thyroid cartilage and at the other end to the arytenoid cartilage. The lower border of this ligament, enclosed in mucous membrane, forms a free crescentic margin, which constitutes the upper boundary of the ventricle of the larynx [12]. This feature seems to have been included in only two other models so far—a 2D model symmetrical about the larynx coronal plane [12] and in a coarse mesh 3D fluid structure model by [5]. Therefore, the current model has focused on the flow dynamics aspect of the problem using a more complex structure.

The CFD software that was used for the numerical work is coming from a package that is included with the CAD software SolidWorks with which the model was shaped. The solver numerically solves the Navier-Stokes equation, and the fluid elements are brick elements. No slip boundary condition on the wall was imposed, and the surface roughness was set to zero. The first of theses assumptions might not be the most accurate simplification to apply considering the nature of the mucosa covering the inner walls of the larynx, but certainly should not greatly affect the results obtained in this study. Adiabatic walls were deemed to bring a sufficiently accurate simplification for the simulation as well.

Variable parameters were the lung pressures, vocal fold frontal angles (VFFAs), and vocal fold opening angles (VFOAs). The various geometrical parameter values used to modify the model shape are shown in Table 1.

Table 1: Model parameters

VFFA	-5˚, 0˚, 5˚, 10˚,15˚
VFOA	0˚, 0.5˚, 1˚, 2˚, 3˚,4˚, 5˚

3.   RESULTS

The simulation highlighted the interaction between the VFFAs and flow rate. This was an expected result, as the shape of the opening facilitates flow the glottal impedance should decrease. Also, the flow rate and maximum velocity increased with increasing the lung pressure, which again is an expected result.

Study of the velocity profiles showed that when the VFFA were of divergent shape (5º, 10º, 15º) the highest velocity—and lowest pressure—occurred at the

inferior part of the vocal fold. The converging shape and flat (VFFA -5°, 0°) proved to bring the higher velocities closer to the superior edge of the vocal fold. The position of the peak flow velocities did correspond with the location of the lowest pressure; the lower pressure zone taking more span of the vocal fold length when the shape was diverging. Flow separation showed to occur at the superior tip of the vocal fold when the shape was flat and converging.

When flow adhered to one of the sides of the glottis—through the Coanda effect—noticeable recirculation occurred in the ventricule found on the same side. This is shown in Figure 1 and 2. Z-axis is the axis that is perpendicular to the plane of the cut and the Y-axis is positive pointing upward. Varying the VFOA did not show any significant effect on the flow behavior other than affecting the flow rate coming through the larynx.
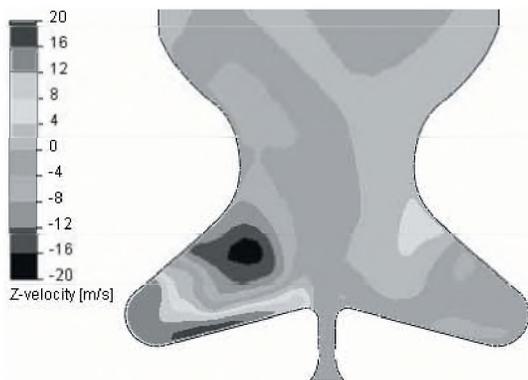
Figure 1: Recirculation in ventricle—VFFA= 0°
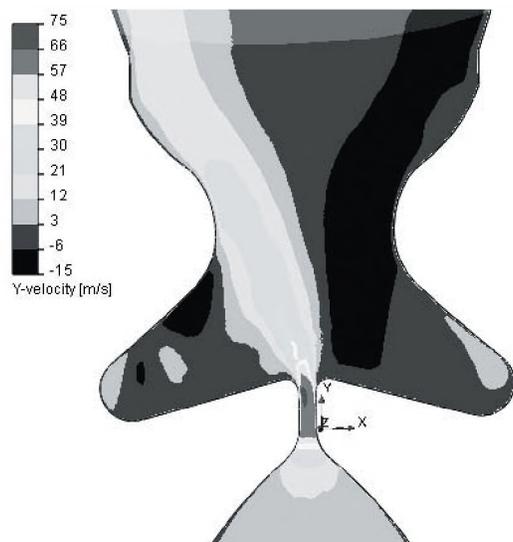
Figure 2: Y-Velocity—VFFA= 0°

4. DISCUSSION

The recirculation occurring in the ventricule when combined with the Coanda effect is enhancing the hypothesis that this effect could be a significant element on the behavior of the ventricular folds. For example, it could explain the action these folds have within a certain range of phonation, especially for certain singing techniques involving the vibration of these folds and screaming.

The relationship between the lowest pressure and the VFFA links the angle with the forced vibration induced by the flow circulating through the glottis. It leads to speculate on the importance of this on the hysterisis between onset and offset phonation pressure. In this context, a more complex simulation can confirm this hypothesis..

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