Pressure Distributions in a Static Physical Model of the Hemilarynx: Measurements and Computations

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Summary: An experimental study of the pressure distributions in an asymmetric larynx, hereafter referred to as a hemilarynx, was carried out at a glottal diameter of 0.04 cm and transglottal pressures of 3, 5, 10, 20, and 40 cm H_2O. In each case, the glottal wall "on the left" was chosen to have an angle of 0° with the midline, and the angle of the glottal wall "on the right" was varied through converging angles of 5°, 10°, and 20° and diverging angles of 5°, 10°, and 20°. The case of two parallel glottal walls, or the uniform glottis, was also examined. With the exception of the 20° convergent case, the pressure distributions for most angles and pressures were bistable; that is, a stable flow situation persisted when the glottal exit flow jet was directed downstream either to the right or to the left in the rectangular "pharynx" tunnel. Bistability also occurred for the uniform glottis. Pressure differences arising from the different directions of the flow jet were often found to be small; however, differences for the diverging 10° case were as large as 7% or 8%, and for the 20° divergent case, 12%. Calculations with FLUENT, a computational package, gave excellent agreement with observed pressures. Implications of the pressure distribution data for the functional similarity of normal and hemilaryngeal phonation, hypothesized by Jiang and Titze, are discussed. In particular, the intraglottal pressures for converging and diverging angles for the hemilarynx were found to be quite similar to those of the full larynx with the same diameter and included angle or twice the diameter and twice the included angle, suggesting that the same mechanism of energy transfer operates in the two cases. Nondimensionalizing the pressure distributions with the transglottal pressures suggests that the shapes of the distributions at $P = 3$, 5, 10, 20, and 40 cm H_2O for a given geometry are similar. The pressure average of these dimensionless distributions may be interpreted as a template at that geometry, a description referred to as successful pressure scaling. When the entire data set is considered, variations from consistent pressure scaling averaged 1.4%, although these variations tend to be somewhat larger near the glottal entrance and for diverging angles of 10° and 20°. Some possible implications of the observed pressures for phonosurgery are discussed.

Key Words: Pressure distributions–Larynx–Hemilarynx–Glottis–Flow rates–Physical model.

INTRODUCTION

Jiang and Titze[1] developed a methodology to study the phonatory properties of canine hemilarynges. By doing so, they could examine the relationship of the oscillations of a single vocal fold against an opposing fixed structure to oscillations during normal phonation. Motivation for their study was twofold: a need to provide useful information for surgeons[2,3] faced with the prospect of immobilizing a dysfunctional vocal fold, and a desire to explore the usefulness of hemilaryngeal phonation to obtain information about the function of the vocal folds not readily available from the study of normal phonation. For example, removal of one of the vocal folds allows better observation of the trajectory of the remaining vocal fold. Further, obtaining measurements of the impact stresses of a single vocal fold oscillating against a Plexiglas plate equipped with appropriate transducers[4] affords an opportunity to better understand vocal fold collisions, their role in normal phonation, and their potential as a cause of vocal fold nodules.[5,6]

Concern arises as to the degree of similarity between the oscillation of a single vocal fold against a fixed structure and the symmetric oscillations of a normal pair of vocal folds. Considering the fact that some hemilaryngectomized patients achieve relatively normal phonation and the results of their experiments with nine excised canine larynges, Jiang and Titze[1] hypothesized a *functional similarity* of hemilaryngeal and laryngeal (normal) phonation. Support for this hypothesis was found in the shape of the lateral excursions of the mobile vocal fold as well as the phase difference observed between the top and bottom edges of the medial surface of this vocal fold, and they surmised that a mucosal wave traveled from the bottom edge of the medial surface to the top edge in hemilaryngeal phonation, just as in laryngeal phonation. In addition, Jiang and Titze[1] observed that the dependence of the fundamental frequencies and the amplitudes of vibration on subglottal pressure were similar for hemilaryngeal and laryngeal phonation. The phonation pressure thresholds and the ranges of subglottal pressures over which the larynges phonated were also similar, but the pressure at which hemilaryngeal phonation became unstable was found to be about 20% higher than the pressure at which full laryngeal phonation became unstable. Moreover, the airflows for the hemilaryngeal case were about a factor of two smaller than for the laryngeal case, and the sound pressure levels differed by a factor of about four. Another potential

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test of the similarity between hemilaryngeal and laryngeal phonation might be carried out by comparing the impact stresses during collisions of the vocal folds[7] with those of a single vocal fold colliding with a Plexiglas plate.[4]

Alipour et al[8] examined the mean pressure-flow relationships as a function of adduction for five excised canine larynges. They found these relationships to be linear with a slight increase in flow resistance at larger flows under conditions of normal phonation. As one would expect, the flow at a given transglottal pressure decreased as the level of adduction increased. These trends also pertained in a study of hemilarynx phonation by Alipour and Scherer,[9] in accord with the hypothesis of functional similarity. This latter study also examined the pressure distributions at several points of a two-dimensional array on the Plexiglas plate used as the opposing vertical structure of the hemilarynx and found complex pressure variations, including a "dynamic bidirectional pressure gradient" along the anterior-posterior surface of the plate. Although it would certainly be a challenging experiment, measurements of the dynamic pressures at corresponding points during phonation of the full larynx could provide an interesting test of functional similarity, if a similar bidirectional gradient was shown to be present.

In a series of papers based on the static Plexiglas model M5 of the glottis, Scherer et al[10,11] and Shinwari et al[12] began a detailed study of the flows and pressure distributions of the oblique glottis (where the center axis of the glottis is not parallel to the midsagittal plane) and comparisons of these properties with their counterparts for the symmetric glottis. Generally, they found the differences between the pressures across the glottis (on the vocal fold surfaces) to be considerably larger for the oblique cases (up to 27% for an included divergent angle of 10° and up to 21% for the uniform case) than for the symmetric case. The pressures on the convergent wall were always higher than those on the opposing wall near the glottal entrance, as one would expect because the flow impinges more directly on this wall. Alipour and Scherer[13] examined the pressure distributions and velocity profiles in a hard plastic hemilarynx model with a long straight wall. They observed that the glottal exit flow proceeded mostly as a jet along the extended straight wall and that the pressures along this wall tended to be lower than those along the other side. They found the location of the peak velocity of the jet occurred in the same relative location for all pressures and diameters observed. They also found that the most turbulent part of the flow occurred in more or less the same relative location for all the observed pressures and diameters.

Scherer et al[10,11] also reported an interesting symmetry-breaking property of the flow pattern for the symmetric glottis. The flow jet did not detach from the glottal walls at the same point on both sides. On one side, it remained closer to the wall, and they spoke of this side as the flow wall (FW, side of tunnel to which flow is directed) and the other side as the non-flow wall (NFW, side of tunnel to which flow is not directed).[14,a] In most cases, the pattern of flow was bistable, because it could be coaxed from one side to the other with a paper guide,[10] where it would remain. One would expect this asymmetric flow pattern to carry a pressure signature, because the side with the faster particle velocities should require more kinetic energy from the pressure field. Indeed, the observed pressures tended to be lower on all or portions of the FW than on the NFW, with the largest difference being about 5% of the transglottal pressure. Cross-glottal pressure differences were observed for transglottal pressures of 5, 10, and 15 cm of H_2O. No difference was observed for the 3 cm case. Shinwari et al[12] replicated these pressure distributions in a different Plexiglas model, which included an upstream stagnation tank. By seeding the airflow with small wetted glass spheres, these researchers succeeded in visualizing the stream of air through the glottis and verified that the flow through the symmetric glottis tended to cling to one side and emerge from the glottis at an angle to the midline for each of the transglottal pressures used in the experiments of Scherer et al.[10,11] Further, Shinwari et al[12] determined that for a diverging angle of 10° the separation point of the flow jet was near the glottal entrance on the NFW, but near the glottal exit on the FW.

In an attempt to further clarify the relationship of the flow and pressure patterns for oblique glottal geometries to those of symmetrical cases, Thapa[15] carried out a systematic examination of the pressure distributions along the medial surfaces of model hemilarynges formed by the seven combinations of plastic inserts shown in Figure 1. Each of these inserts had been used previously with the Plexiglas model M5 wind tunnel either as part of a symmetric pair or in a combination to give an oblique glottis.[10,11] The combinations presented in Figure 1 allow one to form three converging angles (5°, 10°, 20°) between the glottal surfaces, three diverging angles (5°, 10°, 20°), and the uniform, or rectangular, case. The separations of the inserts were adjusted so that the minimal glottal diameter was always 0.0400 ± 0.0002 cm. The hemilarynx always included one straight wall called the *vertical wall* (VW) because of its orientation in a hemilaryngectomized patient. For six of the geometries of Figure 1, the opposing wall is called the *slanted wall* (SW). The uniform geometry of Figure 1D contains two VW's. For all of the geometries of Figure 1, both of the inferior vocal fold surfaces were convergent shapes. Thus, Thapa's model of the hemilarynx did not include the long straight wall of Alipour and Scherer's model,[13] and comparison of the pressure distributions collected with the uniform case of Figure 1D with those of the long straight wall model will give some insight into the consequences of extending the vertical side opposite the healthy vocal fold in a surgical intervention.

Pressure data collected using the geometries of Figure 1 may provide information about the medial forces acting on the oscillating vocal fold during the canine hemilaryngeal studies discussed above. Below, a comparison of the angle dependence of Thapa's hemilaryngeal pressure distributions with that of their counterparts for a symmetric glottis with diameters of 0.04 and 0.08 cm supports the expectation that the driving forces for laryngeal and hemilaryngeal phonation behave in

[a]The FW is the glottal wall (right or left) that lies on the side to which the flow jet heads after leaving the glottal exit. The NFW is the opposite side. Because the jet has separated from the NFW side upstream from its separation in the glottis from the FW side, a stall is expected on the NFW side, as described by Kline.[14]