Intraglottal pressures in a three-dimensional model with a non-rectangular glottal shape

Ronald C. Scherer^{a)}

Department of Communication Sciences and Disorders, Bowling Green State University, 200 Health Center,
Bowling Green, Ohio 43403

Saeed Torkaman, Bogdan R. Kucinski, and Abdollah A. Afjeh

Department of Mechanical, Industrial and Manufacturing Engineering, The University of Toledo,
2801 W. Bancroft Avenue, Toledo, Ohio 43606

(Received 29 September 2009; revised 13 April 2010; accepted 28 May 2010)

This study used a symmetric, three-dimensional, physical model of the larynx called M6 in which the transverse plane of the glottis is formed by sinusoidal arcs for each medial vocal fold surface, creating a maximum glottal width of 0.16 cm at the location of the minimal glottal area. Three glottal angles were studied: convergent 10°, uniform (0°), and divergent 10°. Fourteen pressure taps were incorporated in the upstream-downstream direction on the vocal fold surface at three coronal locations, at the one-fourth, one-half, and three-fourths distances in the anterior-posterior direction of the glottis. The computational software FLUENT was used to compare and augment the data for these cases. Near the glottal entrance, the pressures were similar across the three locations for the uniform case; however, for the convergent case the middle pressure distribution was lower by 4% of the transglottal pressure, and lower by about 2% for the divergent case. Also, there were significant secondary velocities toward the center from both the anterior commissure and vocal process regions (of as much as approximately 10% of the axial velocities). Thus, the three dimensionality created relatively small pressure gradients and significant secondary velocities anteriorly-posteriorly within the glottis. © 2010 Acoustical Society of America.

[DOI: 10.1121/1.3455838]

PACS number(s): 43.70.Bk, 43.70.Aj [DAB]

Pages: 828–838

I. INTRODUCTION

The air pressures within the glottis create forces that participate in the displacement of the vocal folds. Accurate measurement of these pressures and forces is important in understanding basic notions of vocal fold vibration, creating valid dynamic models of phonation, and producing accurate voicing acoustics. Empirically obtained intraglottal pressures using physical models of the larynx, together with theories from fluid mechanics, have historically provided the basic notions of phonatory aerodynamics, as well as the basic equations used in multi-mass models of phonation. The classic equations stem from van den Berg *et al.*¹ (with prior important work performed by Wegel²), with later theoretical and empirical checks and modifications (e.g., by Ishizaka and Matsudaira,³ Gauffin *et al.*,⁴ and Scherer *et al.*⁵). Empirical data using laryngeal models are critical to the accuracy of computer models in that the latter can imbed such data either as empirical modifications of equations or as look-up tables. In addition, empirical data are critical for Navier-Stokes fluid flow solutions within phonation models because they use such empirical data to verify computational accuracy.

Obtaining air pressures on the vocal fold surfaces of humans and excised animals is problematic due to the small size and high speed of motion of the vocal folds. Even dy-

namic models of phonation with slowly moving sides have limitations in this regard. Thus, static models with various laryngeal configurations have been used to obtain intraglottal pressures. The notion that permits the application of these pressures to dynamic computer models has been the sufficiency of the quasi-steady assumption of the physics within the glottal airway first suggested by Ishizaka and Matsudaira³ and Flanagan,⁶ and later supported by Mongeau *et al.*,⁷ Zhang *et al.*,^{8,9} and Kucinski *et al.*,¹⁰ with limitations near glottal closure (Park and Mongeau¹¹).

The shape of the dynamically moving glottis is not uniform anteriorly to posteriorly. The vocal folds converge at the anterior commissure, and attach to the vocal processes posteriorly, the position of the latter determining the posterior separation between the membranous vocal folds. When the vocal processes are touching, the membranous glottis will then take on a curved shape, somewhat half-sinusoidal for the medial surface of each vocal fold, front to back, during the maximum excursion and other phases of the phonatory cycle. Thus, the dynamic glottis is three dimensional, with changes in glottal shape anteriorly to posteriorly, as well as inferiorly to superiorly.

Numerous studies using static or dynamic models of the vocal folds have been performed, e.g., Krane *et al.*¹² (using a driven dynamic model), Erath *et al.*,¹³ Deverge *et al.*,¹⁴ and Li *et al.*¹⁵ These models consider a rectangular transverse section; that is, the frontal cross-section of the glottis at different locations in the anterior-posterior direction was con-

^{a)} Author to whom correspondence should be addressed. Electronic mail: ronalds@bgsu.edu

stant. The larynx three-dimensionality has been addressed in recent studies. Triep *et al.*^{16,17} have studied experimentally and numerically a driven dynamic glottal model, where motion of the vocal folds was mimicked by a complex system of three-dimensional cams. The purpose was to analyze the flow patterns (unsteady vortex shedding) downstream by means of high-speed PIV. Intraglottal pressure measurements were not obtained with the model because of the motion of the glottal surface. Becker *et al.*¹⁸ used an inhomogeneous, self-oscillating synthetic model of the vocal folds to investigate the fluid-structure-acoustic coupling. The results supported the existence of the Coanda effect during phonation, and the flow skewness to one fold and separation from the other. Drechsel *et al.*¹⁹ investigated a symmetric two-layer, self-oscillating, life-size vocal fold model to show the influence of the vocal tract and false folds on the glottal jet. They found that the false folds interfere with the vortex shedding and changes the flow skewness direction. The glottis shape in a self-oscillating model is indeed three-dimensional, but its exact geometry is difficult to determine while the intraglottal pressures cannot be measured.

A number of computational models of the larynx have been developed to study various aspects of phonation, e.g., Bae *et al.*,²⁰ Luo *et al.*,²¹ Tao and Jiang,²² and Larsson *et al.*²³ In these studies, simplified two- or three-dimensional models of the glottis have been investigated, including the flow behavior within and downstream of the glottis.

Although a number of experimental three-dimensional models exist, they are mostly focused on the flow outside rather than inside the glottis. The question is, do the detailed axial intraglottal air pressure distributions at different anterior-posterior positions differ when the glottis takes on a three-dimensional, non-rectangular shape? If so, then realistic modeling needs to take these different pressure distributions into account. In order to explore the three-dimensionality of the flow, a new physical model called M6 was created. This model was used to measure glottal wall pressure distributions and flow rates. For future studies, the model also permits the placement of a model of the arytenoid cartilages posteriorly.

II. METHODS

A. Experimental model

Model M6 is an advancement of the M5 model^{24–26} and is an enlarged physical model of the human larynx with a scaling factor of 7.5 (like M5). The enlargement permits the establishment of an array of pressure taps so that relatively complete pressure distributions can be obtained. The enlargement by the factor of 7.5 also permits highly accurate pressure and flow measurements within the model. Dynamic similitude leads to the model having pressures that are 56.25 times lower than real-life pressures, while the model flow rates are 7.5 times larger.

A general view of M6 is presented in Fig. 1(a). The flow tunnel is 3.83 m long; its rectangular section is 180 mm high and 126 mm wide, with tolerance within 0.5 mm over the whole tunnel length. Half of the tunnel height was occupied by a slab of high density foam, such that the cross-section

FIG. 1. Views of the M6 model: (a) isometric view, (b) top view (all model dimensions in cm). The sinusoidal glottal profile and the tubing manifolds for the pressure taps from a vocal fold can be observed.

used for the present study was 90 mm × 126 mm. The 90 mm dimension is the anterior-posterior dimension, equivalent to a membranous vocal fold length of 1.2 cm, real life. In order to ensure a uniform airflow upstream of the vocal folds (i.e., in the subglottal region), a honeycomb-type flow-straightening section was mounted at the tunnel entrance. The tunnel section downstream of the vocal folds, corresponding to the supraglottal section of the vocal tract, is long enough (2.8 m in the model, or 33.7 cm real life) to prevent end effects at the exit of the device that might affect the intraglottal pressure distribution.

The profiles of the M6 vocal folds in coronal (frontal) view were similar to those used in the M5 model.²⁷ As Fig. 2 shows, the glottis was symmetric, being formed by two identical model vocal folds that were mirror images of each other across the midsagittal plane, and in the transverse plane the profile of the medial surface of each vocal fold was sinusoidal. The anterior and posterior edges of the model folds were in contact, while the maximum distance (i.e., nominal glottal width) was located at the middle of the anterior-posterior span. The glottal width, D_G , was thus twice the lateral concavity (indentation) of each model vocal fold. The symmetrical sinusoidal profile is described by

$$y_p(z) = I_G \sin(\pi z/L),$$

where I_G is the indentation of each fold, L is the anterior-posterior distance (1.2 cm, real life), and z is the coordinate of the anterior-posterior direction ($0 \leq z \leq L$), with the origin at the posterior location.

FIG. 2. Views of the vocal fold pairs showing the anterior ends on the left and isometric views on the right: (a) convergent, (b) uniform, and (c) divergent configurations of the glottis.

As the vocal fold shape changes during the phonatory cycle (from convergent to uniform to divergent), a large number of instantaneous frontal profiles can be considered for a static investigation. In the present work, three representative frontal profiles, namely convergent 10° , uniform 0° , and divergent 10° , were chosen, with an indentation of 0.08 cm (real life) for each vocal fold such that the glottal width, D_G , was 0.16 cm (real life) at the location of the smallest glottal transverse (projected) area. The 0.16 cm diameter at the center of the anterior-posterior span of the glottis was located near the glottal exit for the convergent case, at the glottal entrance for the divergent case, and from entrance to near exit for the uniform case. The ratio of the anterior-posterior distance to the maximum glottal width was thus 7.5. Figure 2 shows frontal end and isometric views of the vocal folds for (a) convergent, (b) uniform, and (c) divergent geometries.

One of the model vocal folds of each pair had pressure taps that were used to measure intraglottal pressures on the walls of the vocal folds. The glottal wall pressures were measured using three rows of 14 pressure taps, located at three different coronal cross-sections, viz., the midsection and two sections symmetrically located 0.3 cm (real life) from the mid-section. The pressure taps, therefore, were at the anterior-posterior $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ distances along the vocal folds. The glottal width for the minimal glottal area transverse plane at the $\frac{1}{4}$ and $\frac{3}{4}$ sections (the “quarter sections”) was 0.113 cm. The taps were numbered in the axial (flow) direction (Fig. 3) such that tap #6 corresponded to the glottal entrance. Taps #1–5 were on the inferior vocal fold surface, taps #6–11 along the straight portion of the vocal fold, tap #12 on the surface at the middle of the glottal exit expansion curvature, and taps #13 and #14 on the superior horizontal surface of the vocal fold adjacent to the glottal exit. Additional pressure taps were located on the right tunnel wall in the supra-glottal region [taps #0 and #15–19 in Fig. 1(b)]. The downstream tap (tap #0) was used to adjust and monitor the transglottal pressure. The rest of the additional taps helped to monitor the wall pressures immediately downstream of the vocal folds. It is noted that in this experiment the false vocal folds were not included. The pressure taps were built perpendicular to and flush with the glottal surface.

FIG. 3. Pressure taps on the vocal folds. There are three rows of taps on the vocal fold surface (Anterior, Middle and Posterior), each row containing 14 taps. Tap #6 is located at the entrance to the glottis, tap #12 is on the mid-region of the rounded surface of the glottal exit, while taps #13 and #14 are on the top of the vocal fold.

The glottal pressure taps had a diameter of 0.0762 cm (0.030 in), corresponding to 0.01 cm (real life), less than a tenth of the glottal gaps at each tap. Thus, the taps were not expected to alter or disturb the pressures or the flows within the glottis. The axial position of the taps in all three rows was identical.

The entrance and exit radii for the vocal fold pieces were as follows: for all pieces, the radius at glottal entrance was 0.15 cm; the exit radius for the convergent shape was 0.0841 cm, for uniform 0.0987 cm, and for divergent 0.119 cm.

A schematic of the M6 instrumentation is presented in Fig. 1(b). Air flow was driven by generating a negative gauge pressure downstream (by using a vacuum pump). The 42 pressure taps on the model vocal folds and the 5 pressure taps located on the lateral wall were connected to a pressure scanner (Scanivalve SSS-48C MK4) by silicon tubing, which was connected to a pressure transducer (PT1). The pressure scanner is a computer-controlled switching device which connects each inlet port to a pressure transducer. Another pressure transducer, PT0, was connected to the transglottal reference pressure tap. PT0 and PT1 were two very low pressure transducers (DP103, Validyne Engineering Sales Corp., Northridge, CA). The uncertainty of the pressure measurements was estimated to approximately 5 Pa (real life), based on the manufacturer’s specifications as well as on data replication. A signal conditioner (SC, model CD15, Validyne Engineering) for each transducer was wired to a data acquisition card (NI USB-6221). The pressure voltage values were

sampled at a rate of 100 samples/s. A Labview computer program was designed for data acquisition and processing. A certain amount of time was necessary for the pressure to stabilize within the tubing leading from the tap to the pressure sensor. The length of the tubing was made as short as possible to minimize this interval. In this study, 60 s were used as the stabilization time, and 1500 samples were acquired during the next 15 s for each tap. The average value of the samples was reported as the measured value. The flow rate was measured by a rotameter (Fischer-Porter 10A1027) with a range of 20–1000 l/min. The accuracy of the flow measurements was estimated to be approximately 6 cm³/s (real life).

B. Computational method

Numerical simulations of the flow through the glottal configurations introduced in Section II A were performed. They provided a potential verification of both the experimental data and the usefulness of the computational technique for analyzing the flow through the three dimensional glottis. The Navier-Stokes equations were solved numerically by using the commercial CFD package FLUENT, a finite-volume solver. This software has been successfully used for the study of the flow in both static^{24,26} and moving¹⁰ glottal configurations. It has been shown to adequately predict glottal wall pressures, as well as glottal flow rates.

The glottal flow is usually considered incompressible, based on the assumption that the airflow velocities are generally low, i.e., the Mach number is $Ma < 0.3$. In the present work transglottal pressures up to 2.453 kPa (25 cm H₂O) were investigated, such that the Mach number, based on a speed of sound of 340 m/s, were less than 0.2 (see Table III). The use of an incompressible solver was thus justified. Numerical experiments with the ideal gas compressible model for 2.453 kPa have shown only negligible differences when compared with the incompressible model. The implicit version of the pressure-based solver with SIMPLEC pressure-velocity coupling was used for the present study. Second order schemes were chosen in FLUENT for both momentum and pressure.

The laminar flow model was selected for the numerical simulations, consistent with previous studies performed on two-dimensional models^{10,24} where the maximum transglottal pressure was 1.472 kPa (15 cm H₂O). The laminar model is justified experimentally for the flow inside the glottis, for both static²⁶ and dynamic (oscillating) models. Kucinski *et al.*¹⁰ performed laser flow visualizations inside a driven dynamic model that showed the flow is laminar even for an oscillation frequency of 112 Hz. Neubauer *et al.*²⁸ showed that a laminar region exists immediately downstream of the glottis in a self-oscillating physical model of the vocal folds. Further downstream of the glottis the jet transitions to turbulence; however, this region was not included in the computational domain, since the wall pressures are generally equal to the supraglottal pressure in the model. The laminar flow assumption is confirmed *a posteriori* by the fact that the dimensionless intraglottal pressures do not change for the

FIG. 4. Three-dimensional structured mesh of the computational glottal model (one quarter of the low-resolution mesh is shown).

entire range of transglottal pressures used in this study (see also Section IV A).

Pressure boundary conditions were imposed for all simulations, with the nominal transglottal pressure as the inlet gage pressure and zero as the outlet gage pressure. The convergence criteria were mass and velocity relative residuals less than 10^{-5} , and inlet-to-outlet mass imbalance less than 10^{-10} kg/s. A structured mesh topology of hexahedral cells was used for all cases. In the experimental setup the model vocal folds were in contact at both the anterior and posterior locations (see Fig. 2). The computational mesh becomes degenerate on the contact edges, with a negative impact on the accuracy of the simulations. In order to eliminate this problem, the vocal folds were separated by a very small gap (i.e., 0.03 mm) at the ends instead of coming to a very sharp corner of the computational model. The small size of the gap was expected to alter the computational results only to a negligible extent. The meshing was performed such that cells close to the glottal walls were finer than those near the longitudinal axis, in order to better account for velocity gradients at the wall. The computations were performed on a complete mesh (symmetry boundary conditions were avoided because possible jet asymmetry would not have been captured). Figure 4 shows a typical mesh for a three-dimensional glottis (the uniform, 0.16 cm case is represented; only one quarter of the mesh is shown in order to avoid cluttering the figure). The M6 experiments have shown that the wall pressure drop downstream of the glottis is negligible. This permits the limitation of the computational domain to a short distance downstream of the vocal folds (reducing the computational effort, while retaining the observed laminar region). Since the anterior-posterior (i.e., vertical direction in Fig. 4) velocity gradients were expected to be smaller than those in the lateral and axial directions, the mesh density in this direction was generally lower.

Three types of grids were used in simulations. The coarse grids contained between 250,000 and 475,000 cells. The medium mesh was derived from the coarse grid such that the first two layers of cells adjacent to the wall were refined. The finest mesh was created by splitting all the cells in the coarse mesh. Table I presents the characteristics of each mesh for all cases (uniform, convergent, and divergent glottal shapes). These grids of increasing density were used

TABLE I. Characteristics of the computational grids used for the FLUENT simulations.

Mesh type	Convergent 10°		Uniform		Divergent 10°	
	Cells	Nodes	Cells	Nodes	Cells	Nodes
Coarse	330 240	352 755	252 120	273 494	473 580	501 774
Medium	712 160	820 749	602 316	702 910	936 000	1 067 930
Fine	2 641 920	2 731 365	2 016 960	2 101 799	3 788 640	3 900 731

to verify that the results are grid-independent. The simulations were run on the OSC (Ohio Supercomputer Center) clusters, as well as on a Linux 64-bit machine.

III. RESULTS

Transglottal pressures of 0.294, 0.491, 0.981, 1.472, 1.962, and 2.453 kPa (i.e., 3, 5, 10, 15, 20, and 25 cm H₂O) were investigated in this study. Figure 5 presents both the experimental results of this study (symbols), and the computational results from FLUENT (lines), for a transglottal pressure of 0.294 kPa for the glottal angles of 10° convergent, 0° (uniform), and 10° divergent. There are three sets of data points for each glottal angle corresponding to the position of the pressure taps in the inferior-superior direction, namely, midway (mid-coronal) along the vocal fold, and 0.3 cm anterior and posterior to the mid-location. For all shapes, the pressures on the inferior vocal fold surface (taps #1–5) decrease as the cross sectional area of the region reduces. The pressures at corresponding taps for both the anterior and posterior distributions are nearly identical (due undoubtedly to the symmetry of the geometry relative to the midcoronal plane of the glottal airway).

Intraglottal pressures for the convergent shape decrease from tap #6 (at the glottal entrance) toward the glottal exit, are lowest at tap #11 where the minimal glottal diameter is located, and then rise, consistent with pressure recovery in

FIG. 5. (Color online) Experimental (symbols) vs. computational (lines) comparison for the convergent 10°, uniform 0°, and divergent 10° cases, glottal diameter of 0.16 cm (real life), for transglottal pressures 0.294 kPa (i.e., 3 cm H₂O). The presented numerical results correspond to the finest mesh in Table I.

the short curvature toward the glottal exit proper, with pressures at tap #12 nearly equal to the pressures on top of the vocal folds (taps #13 and #14) near the glottal exit. Relative to the pressures for the convergent case, the middle section pressure distribution consistently shows values less than for the other two distributions up to tap #9, beyond which the values for all three locations coincide. The pressure difference between the distributions at tap #6 is 11 Pa, or 4% of the transglottal pressure drop, suggesting that, at the glottal entrance (and upstream on much of the inferior glottal surface), a smaller lateral force (“push”) acts on the wall at the middle of the vocal fold than at the anterior and posterior sections. The “push” difference, however, is small, and the pressures become essentially the same on the vocal fold surface starting near the downstream center of the glottis at all three locations. The comparison with experimental data show that the FLUENT values (the continuous lines in the figure) are excellent approximations for the convergent case. The computational results also suggest a slight dip in the pressures just before tap #6, and a greater pressure dip just past tap #11.

The pressure distributions for the uniform glottis in Fig. 5 show a local minimum at tap #6, rising to tap #7, and then decreasing to tap #11, with the pressure recovery again at the end of the glottis due to the rounded exit. It is noted that even though the duct is uniform, the diameter is 0.16 cm (real life) at the maximum glottal width, with a glottal duct length in the inferior-to-superior direction of 0.3 cm. Thus, the glottal duct is not aerodynamically long relative to setting up a linear pressure drop satisfying a Poiseuille distribution, but instead produces the pressure dip at tap #6. Contrary to the convergent case, the pressures at tap #6 are approximately equal for the distributions at the three locations (anterior, middle, posterior); from tap #7 to tap #11, pressures for the middle distribution are slightly higher than for the other two distributions (by at most 9 Pa, or 3% of the transglottal pressure).

Relative to the divergent 10° case in Fig. 5, the relation among the pressure distributions is similar to the convergent case in that the center pressure at (and upstream of) tap #6 is lower than for the pressure in the anterior and posterior sections. The difference in pressure is 6 Pa, or 2% of the transglottal pressure at tap #6. The rise in pressure from tap #6 to the glottal exit, using the middle distribution, was 78 Pa, or 27% of the transglottal pressure. The computational predictions are slightly larger than both pressure drops at tap #6, the location of the greatest change in contour in the model (i.e., at the divergence entrance), but match the empirical data better downstream of tap #6.

The comparison of measured and computational flow estimations are shown in Table II. The greatest difference between empirical and computational results (using the fine mesh) was 4.7% for the convergent case 0.294 kPa case. Overall the average difference between experimental and FLUENT data was 1.7% (standard deviation of 1.1%). This suggests that FLUENT predicted the flow rates well.

The intraglottal pressure distributions for all the transglottal pressures ($\Delta p_T = 0.294, 0.491, 0.981, 1.472, 1.962$, and 2.453 kPa), shown in dimensionless format in Fig. 6, are

TABLE II. M6 glottal flow rates (in cm³/s, real life) for different values of transglottal pressure, Δp_T : comparison between experimental data and computational results. The computational results are presented for three grids (see Table I): coarse (C), medium (M), and fine (F).

Δp_T (kPa)	Convergent 10°				Uniform				Divergent 10°			
	Exp'l	(C)	Comp (M)	(F)	Exp'l	(C)	Comp (M)	(F)	Exp'l	(C)	Comp (M)	(F)
0.294	257.8	268.9	270.5	269.9	255.6	256.0	257.0	256.3	277.8	286.5	287.6	287.3
0.491	344.4	349.3	351.8	351.0	333.3	334.8	336.3	335.7	366.7	372.7	375.0	374.2
0.981	488.9	497.2	501.4	500.2	477.8	476.9	483.0	482.8	522.2	529.7	535.4	533.3
1.472	611.1	610.9	616.4	614.7	588.9	593.0	596.2	596.2	633.3	639.3	652.5	640.3
1.962	700.7	707.0	713.2	711.2	677.8	688.4	692.2	690.4	722.2	733.6	752.0	738.2
2.453	793.3	791.7	798.5	796.3	766.7	772.7	777.0	774.2	788.9	817.2	837.9	800.9

typical for the three glottal shapes. The dimensionless pressure was calculated as $P=p/\Delta p_T$. The following observations are made: (a) The shape of the experimental and computational pressure distributions are similar to the 0.294 kPa case presented above, for each of the glottal angles. (b) For the convergent case, the difference between the middle and the other pressure distributions (i.e., anterior and posterior sections) at the glottal entrance tap #6 are similar, ranging from 4.2% to 5.2% of the transglottal pressure (mean of 4.9%, standard deviation of 0.34%). (c) For the uniform case, the pressure at glottal entrance tap #6 is lower than at tap #7 for the distribution at all three locations, and the largest intraglottal pressure difference between the middle and other two locations is again similar and small (with a range of 2.0% to 3.2% of the transglottal pressure, mean of 2.7%, standard deviation of 0.42%), with the middle distribution values higher than the other two distribution values. (d) The middle distribution pressure values at tap #6 for the divergent cases were consistently lower than for the distributions at the other two locations, with a range of difference from 2.6% to 7.4% of the trans glottal pressure (mean of 5.6%,

standard deviation of 1.7%). (e) The pressure rise (recovery) between tap #6 and tap #14 for the divergent glottis was also similar among the five different trans glottal pressures, with a range of 26% to 30% (mean of 28%, standard deviation of only 1.5%).

IV. DISCUSSION

A. Pressures and velocities at different coronal sections

The Reynolds number is calculated as $Re=UD_H/\nu$, based on the hydraulic diameter of the glottis, $D_H=4A/P$, and the kinematic viscosity of air, $\nu=1.5\times 10^{-5}$ m²/s. Given the sinusoidal geometry of the model, the minimum transverse area is $A=2D_G L/\pi$ and its perimeter is $P=2\int_0^L[1+(\pi D_G/2L)^2\cos^2(\pi y/L)]^{1/2}dy$, such that D_H is 0.2 cm. The Reynolds number is in the range $2800 < Re < 8500$, which is common for phonation. Despite the relatively larger values of Re , flow visualizations (e.g., Shinwari *et al.*,²⁶ Kucinski *et al.*,¹⁰ Neubauer *et al.*²⁸) showed laminar flow inside the glottis for both static and oscillating larynx models. However, the flow was observed to become turbulent further downstream of the glottis. The laminar glottal flow regime explains the quasi-identical dimensionless intraglottal pressure distributions shown in Fig. 6 for any given geometry and coronal section. This suggests that the flow regime does not change with the transglottal pressure.

While the pressures can be measured experimentally on the glottal walls, it is more difficult to measure velocities inside the M6 sinusoidal glottis because of the limited optical access. This difficulty is common for all non-rectangular models, where the PIV technique has been used only downstream of the glottis.^{16,17} The velocity fields, together with the complete pressure fields, were obtained by means of CFD simulations. Since the experimental wall pressures and flow rates are well matched computationally, one can infer that the velocities are also correctly predicted throughout the glottis. The calculated midsagittal velocities at the middle, anterior quarter, and posterior quarter coronal sections for the three glottal shapes at the minimal glottal locations are presented in Table III. The first observation is that the velocities (in m/s, real life values) are slightly greater away from midline. The anterior (or posterior) locations have axial velocities 1.15%–3.54% higher than at the midline. This finding is consistent with the PIV velocity measures of Khosla *et al.*,²⁹

FIG. 6. (Color online) Non-dimensional comparison of experimental data (symbols) vs. computational results (lines) for the convergent 10°, uniform 0°, and divergent 10° cases, glottal diameter of 0.16 cm (real life), for transglottal pressures of 0.294, 0.491, 0.981, 1.472, 1.962, and 2.453 kPa (i.e., 3, 5, 10, 15, 20, and 25 cm H₂O). For all geometries and pressures the experimental data are presented with (○), (△) and (□) in mid, anterior and posterior sections, respectively. The numerical results correspond to the finest mesh in Table I.

TABLE III. Computational axial velocities in m/s (real life) at the middle, anterior- and posterior quarter sections for the three glottal shapes at the minimal glottal locations, for two values of the transglottal pressure, $\Delta p_{T,1}=0.294$ kPa, and $\Delta p_{T,2}=2.453$ kPa. The M6 computational results correspond to the finest grid in Table I.

	Convergent 10°		Uniform		Divergent 10°	
	$\Delta p_{T,1}$	$\Delta p_{T,2}$	$\Delta p_{T,1}$	$\Delta p_{T,2}$	$\Delta p_{T,1}$	$\Delta p_{T,2}$
Ant., Post.	21.57	61.57	20.20	57.37	22.86	66.53
Middle	21.33	60.82	19.66	57.34	22.32	64.67

who measured velocities 0.3 cm from the glottal exit. They found that velocities in the midsagittal plane of the glottis were typically slightly greater away from the anterior-posterior center plane (refer to their Fig. 3). The greater velocity found in the anterior portion of the glottis compared to other locations more posterior by Berke *et al.*,³⁰ Alipour and Scherer,³¹ and Bielamowicz *et al.*³² (who found large increases anteriorly) may be due more to eccentricity of the glottis because of the presence of the arytenoid cartilages or geometry asymmetries of the vocal folds.

B. Two dimensional (rectangular) vs. three dimensional glottal models

The glottis is rectangular in the transverse plane in many prior models (henceforth referred to as 2D models), such that the coronal section is identical at any location along the anterior-posterior direction. Due to the large ratio of anterior-posterior distance to glottal opening, the glottal flow can be considered to be essentially two-dimensional.^{24,26} This section compares the M6 results to the rectangular configuration in order to show the significance of the three-dimensional effects on the wall pressures. Here the two-dimensional version of FLUENT was used to solve the 2D (rectangular)

cases whose geometry correspond to both the 0.16 cm opening of the middle coronal section of M6, and the 0.113 cm opening of the anterior or posterior quarter coronal sections of M6. The following discusses the results for two glottal shapes (i.e., 1.2 cm × 0.16 cm and 1.2 cm × 0.113 cm, rectangular form), compared to the M6 sinusoidal-sided, non-rectangular shape, at identical coronal cross-sections. The method of using two-dimensional CFD simulations for rectangular models was validated in prior work.^{10,24,25,33}

Figure 7 presents the intraglottal pressures for sinusoidal (i.e., M6) and for the rectangular glottis for the six configurations, i.e., convergent 10°, uniform, and divergent 10°, in the middle (0.16 cm) and anterior/posterior coronal (0.113 cm) cross-sections. The 2D pressure drops for the 0.16 cm glottis are consistently larger than those obtained for M6 in middle coronal cross section. The largest differences for all cases occur just upstream of the glottal entrance, near the end of the convergent inlet zone. For the convergent and uniform geometries, the 2D 0.113 cm pressure distributions are relatively close to both the M6 anterior and M6 midsection distributions throughout the glottis. The convergent glottis velocity profiles in the glottal entrance and near the glottal exit are consistent with these results, as shown in Fig. 8. The entrance velocities for the 2D 0.16 cm section are larger than for the 3D (M6) middle section, which is consistent with the larger pressure drop.

FIG. 7. Comparison between the pressure profiles in M6 (mid-coronal and anterior coronal plane) with the pressure profiles in similar two-dimensional geometries, for a transglottal pressure of 1.472 kPa (15 cm H₂O). The M6 mid-coronal results are represented with a continuous line, and M6 anterior coronal with a dashed line. The two-dimensional pressures are represented with dash-dot line (—) for the mid-coronal, and dash-dot-dot (---) line for the anterior coronal plane. The uniform profiles (“UNI”) are identified by the symbol (○), and the divergent ones (“DIV”) by (Δ). No symbol is used for the convergent profiles (“CON”).

FIG. 8. Axial velocity profiles in mid- and anterior coronal planes at glottal entrance (tap #6 position, $x=0$) and near exit (tap #11 position) (symbol ○) for the convergent case. Comparison between M6 and the corresponding two-dimensional cases, for a transglottal pressure of 1.472 kPa (15 cm H₂O). The M6 mid-plane results are represented by a continuous line, and the M6 anterior plane by a dashed line (—). The two-dimensional pressures are represented with dash-dot line (—) for the mid-plane, and dash-dot-dot (---) line for the anterior plane. The lines with symbols are for the near-exit velocity profiles.

TABLE IV. Comparison between the calculated M6 flow rates (in cm³/s, real life), and flow rates calculated in the two-dimensional geometries corresponding to the anterior and middle planes in M6, for different values of transglottal pressure, Δp_T . The M6 computational results correspond to the finest grid in Table I.

Δp_T (kPa)	Convergent 10°			Uniform			Divergent 10°		
	M6	2D (Ant)	2D (Mid)	M6	2D (Ant)	2D (Mid)	M6	2D (Ant)	2D (Mid)
0.294	269.9	296.6	418.1	256.3	289.2	411.4	287.3	337.7	465.4
0.491	351.0	384.8	542.3	335.7	377.7	535.7	374.2	440.9	606.5
0.981	500.2	546.8	770.2	482.8	541.4	765.0	533.3	631.7	867.2
1.472	614.7	671.2	945.0	596.2	667.6	941.4	640.3	778.7	1068.1
1.962	711.2	776.4	1092.2	690.4	774.3	1090.4	738.2	902.9	1237.8
2.453	796.3	869.3	1221.8	774.2	868.4	1221.7	800.9	1012.5	1387.6

Table IV presents the flows rates in the 2D section cases and the corresponding M6 sections. For the convergent 10° 2D larynx with the midsection diameter (0.16 cm), the flow rates are approximately 54% larger than for M6 for all the transglottal pressures, while for the 2D larynx with the anterior section diameter (0.113 cm) the flow rates are only approximately 9.5% larger than for M6. For the uniform geometry, the flow rates in the 2D cases with mid- and anterior section diameters are approximately 60% and 12% larger, respectively, than for M6. The largest differences occur for the divergent 10°, where the flow rates for the 2D midsection are between 62 and 73% larger than for M6, while for the 2D anterior section they are between 17.5 and 26% larger than for M6. The pressure and flow rate data suggest that the overall glottal flow resistance for the M6 sinusoidal geometry is greater than for a rectangular geometry with the same nominal opening diameter. This behavior is related to the minimum transverse area (usually known as the “projected glottal area”), which for M6 is 0.122 cm² for all three glottal angles. For the rectangular with 0.16 cm and 0.113 cm openings, the minimum transverse areas are 0.192 cm² and 0.136 cm², respectively, for the anterior-posterior length of 1.2 cm.

One can observe that flow rate, Q , and area, A , are proportional for the same pressure drop. The area ratio between the 2D midsection (0.16 cm) and M6 was 0.192 cm²/0.122 cm² or 57% higher, and for the 2D anterior section (0.113 cm) and M6 midsection 0.138 cm²/0.122 cm² or 11% higher. These percentages match the flow rates well for the convergent and uniform glottis. This proportionality suggests that if the same mean velocity, $U=Q/A$, is maintained, then the Bernoulli equation, $U=\sqrt{2\Delta p/\rho}$, may be applied for the same pressure drop, Δp . Figure 7 shows that for the convergent geometry the maximum values of pressure drop occur just upstream of the glottal exit (at about 2 mm), and are similar for all sections (either 2D or M6), which explains the apparent success of Bernoulli for this case. For the uniform geometry, Fig. 7 shows that the maximum pressure drop occurs slightly upstream of glottal entrance ($x=0$ mm), and shows modest variations between different 2D or M6 sections, such that again Bernoulli appears to be reasonable. It could be inferred that Bernoulli could be used to estimate the flow rates for the

convergent and uniform glottal shapes. However, much larger variations of Δp are observed for the divergent glottal shape, such that the *ad-hoc* application of the Bernoulli equation would lead to severe overpredictions of the flow rate. This shows that, in general, the Bernoulli equation fails to produce accurate estimations of flows through the three-dimensional glottis. More accurate analytic models exist,^{14,34} but they are less intuitive than the Bernoulli equation, and applicable only to two-dimensional (rectangular) geometries.

One can also conclude that it is generally incorrect to assume that a rectangular model can provide reliable data for a three-dimensional glottis having the same area. It is probable the inaccuracies are less for smaller minimum mid-coronal openings (the value of 0.16 cm used in the current work represents a relatively large glottal opening).

C. Comparison with dynamic pressures

Alipour and Scherer³⁵ examined pressures opposite the medial vocal fold on a vertical flat plate in a hemilarynx set up. Pressure taps on the plate were positioned along both the vertical (flow) direction and the anterior-posterior direction. Their results (their Fig. 9) suggest qualitatively similar findings to those of the current study, whereby (1) the middle

FIG. 9. Anterior-posterior velocity profiles in the midsagittal plane of the M6 convergent 10° glottis, at three axial locations: $x=0$ cm (i.e., glottal entrance), 0.1 cm and 0.2 cm. The transglottal pressure is 1.472 kPa (15 cm H₂O).

FIG. 10. Velocity profiles in a transverse section located at the glottal exit ($x=0.3$ cm), for a transglottal pressure of 1.472 kPa (15 cm H₂O), for all three geometries: convergent 10° uniform, and divergent 10°. The dotted lines trace the projected minimal glottal perimeter.

section pressure tap recorded greater pressure drops than taps more anterior and more posterior near glottal entry for a divergent glottis, and (2) nearly equal (midsection pressures slightly less) for convergent and nearly uniform shapes. The gross glottal angle is inferred here from the timing of their pressure signals. Although qualitatively similar in those ways, the more anterior and posterior pressures were always positive, and the exact dynamic shaping of the vocal fold is unknown.

D. Secondary flows

In a rectangular glottis the flow is two-dimensional, so that velocities have significant components in coronal cross-sections only, and the flow is analyzed in the x - y plane. The axial velocity (i.e., x -velocity) is the main velocity component, corresponding physiologically to the upward (sub glottal-to-supraglottal) direction. The M6 glottis is sinusoidal on each side, and the anterior-posterior component of the velocity (z -velocity) cannot be neglected. This component is responsible for secondary flows in the three-dimensional glottis.

The secondary flows were determined by performing CFD simulations. Figure 9 presents the velocity profiles in the posterior-anterior symmetry plane of the M6 convergent 10° glottis, at three axial locations: $x=0$ cm (i.e., glottal entrance), 0.1 cm, and 0.2 cm (just before the exit rounding of the vocal folds), for a transglottal pressure of 1.472 kPa (15 cm H₂O). This anterior-posterior velocity is zero at the mid-coronal section (because of the symmetry across the mid-coronal plane), but in the anterior and posterior quarter sections the magnitude of this velocity is significant, approximately 4 m/s for the glottal entrance, increasing downstream to 4.5 m/s. This velocity within the glottis toward the center of the glottis represents approximately 10% of the magnitude of the axial velocity out of the glottis in the midsection. Higher velocities occur near the anterior and posterior extremities of the glottis. Figure 10 shows qualitatively the velocity vectors in a transverse section of the three models (convergent, uniform, divergent) at the glottal exit;

FIG. 11. Velocity vectors and streamlines in the mid-sagittal plane for the convergent 10° (a), uniform (b), and divergent 10° (c) geometry. The glottal diameter is 0.16 cm (real life), and the transglottal pressure is 1.472 kPa (15 cm H₂O).

here the case for a transglottal pressure of 1.472 kPa (15 cm H₂O) is presented for illustration. It can be observed that the velocity profiles are relatively uniform across the glottis up to about 0.4 cm from the midsection, and become increasingly non-uniform toward the extremities. The observations above indicate that three-dimensionality of the flow is significant, despite the apparently large aspect ratio (i.e., 7.5) of the anterior-posterior length to glottal opening. Consequently, the velocity vectors in the mid-sagittal section are oriented toward the mid-coronal (symmetry) plane, as shown in Fig. 11. The streamlines indicate that separation occurs at

the anterior and posterior ends. The separation occurs upstream of the glottal exit for the uniform and divergent geometries, and slightly downstream of the exit for the convergent geometry. The confinement of the glottal jet in the midsagittal plane toward the center was observed in the PIV work by Khosla *et al.*²⁹

V. CONCLUSIONS

The glottis with curved (sinusoidal) sides makes a difference relative to intraglottal pressures, although the pressure differences (mid, anterior, posterior) do not rise above about 7% of the transglottal pressure. The mid location pressures tended to be lower for the convergent and divergent shapes near glottal entry, but similar for the uniform case at entry, and about the same within the glottis after an axial distance of about one-third into the glottis. Thus, near the glottal entry slightly less vocal fold “push” (convergent) and slightly more “pull” (divergent) may exist at the midsagittal plane, compared to locations anteriorly and posteriorly. This conclusion is supported qualitatively by dynamic glottal pressures given in Alipour and Scherer.³⁵

The axial velocities in off-center coronal sections were similar to the mid-coronal section axial velocities (being only about 1%–4% higher). On the other side, the magnitude of the center-directed velocity in the off-center sections was significant, being on the order of 10% of the main (axial) velocity in the investigated sections (i.e., anterior and posterior quarter coronal sections). These secondary flows that move toward the center from the more anterior and posterior positions support non-axial exit flows shown in some PIV images in Khosla *et al.*²⁹

A generalization of these results from the 3D laryngeal model M6 to the dynamic human larynx is that there are pressure and velocity gradients in both the axial (upstream-downstream) and longitudinal (anterior-posterior) directions, with primary gradients axially and secondary gradients longitudinally. When eccentricity is present by introducing the posteriorly placed arytenoid cartilages (with closed posterior glottis), the longitudinal gradients may increase, an hypothesis currently being studied. The model here used a mid-glottal diameter of 0.16 cm. The use of smaller diameters may reduce the secondary pressures and velocities.

The current study of the more realistic sinusoidal model of the glottis suggests that results from the rectangular models are still useful in that they generally provide the correct overall shape of intraglottal pressures. However, care would need to be taken when applying the rectangular results to three-dimensional, non-rectangular glottal shapes, especially for large values of the mid-coronal glottal opening. It appears that more realistic, non-rectangular laryngeal geometries are required in research programs of basic laryngeal function to establish benchmark empirical data.

ACKNOWLEDGMENTS

This research was supported by NIH Grant No. 2R56DC003577. The computational work was supported in part by an allocation of computing time from the Ohio Supercomputer Center.

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