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Time-dependent pressure and flow behavior of a self-oscillating laryngeal model with ventricular folds

Fariborz Alipour and

Department of Communication Sciences & Disorders, 334 E WJSHC, The University of Iowa, Iowa City, Iowa 52242

Ronald C. Scherer

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

Abstract

Objective—The purpose of the study was to better understand the pressure-flow behavior of a self-oscillating vocal fold model at various stages of the glottal cycle.

Methods—An established self-oscillating vocal fold model was extended to include the false vocal folds and was used to study time-dependent pressure and velocity distributions through the larynx (including the true and false vocal folds). Vocal fold vibration was modeled with a finite element method (FEM), laryngeal flow was simulated with the solution of unsteady Navier-Stokes equations, and the acoustics of the vocal tract was modeled with a wave reflection method.

Results—The results demonstrate realistic phonatory behaviors and therefore may be considered as a pedagogical tool for showing detailed aerodynamic, kinematic, and acoustic characteristics. The true vocal folds self-oscillated regularly with reasonable amplitude and mucosal waves. There were large pressure gradients in the glottal region. The centerline velocity was highest during glottal closing and sharply dropped near the center of the flow vortex. The average centerline velocity was about 25 m/s in the glottal region. The transglottal pressure was higher during glottal closing when the glottal shape was divergent and pressure recovery was present within the glottis. The centerline velocity increased as expected throughout the convergent glottis, tended to decrease throughout the divergent glottis, and decreased past the true vocal folds within the ventricle-FVF region.

Conclusions—This model produces realistic results and demonstrates interactions among phonation variables of a highly instructive nature, including the influence of the false vocal folds.

Please address all correspondence to: Fariborz Alipour, Ph.D., Tel: (319) 335-8694, Fax: (319) 335-8851, alipour@iowa.uiowa.edu. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute on Deafness and other Communication Disorders or the National Institutes of Health.

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Keywords

glottal pressure distribution; laryngeal velocity pattern; finite-element model; false vocal folds

INTRODUCTION

One of the most useful functions of laryngeal models is to show complex relationships among numerous variables that are not simultaneously measurable within the human. Modeling can therefore be a convenient and powerful tool to investigate complex functions and educate students. With this in mind, the goal of this report was to show complex behavior and phonatory signals using a validated, complex computational model of phonation. The model includes the false vocal folds to add further reality to the model.

Since the ventricles and false vocal folds (ventricular folds) are included as a new enhancement to the model, a summary of their reported effect will be given next.

The ventricular folds, also known as the false vocal folds (FVFs), are thick bands of tissue lying above the true vocal folds (TVFs), and separated from them by the laryngeal ventricle air space (the ventricles of Morgagni). The FVFs have important non-phonatory functions, such as closure of the laryngeal lumen during deglutition and other primitive reflexes during coughing, gagging, etc.¹ During phonation, glottal flow passes by the ventricles as a pulsating jet that influences the air pressures in the ventricles and in turn may affect the aerodynamic forces on both the TVFs and the FVFs.² The aerodynamic and biomechanical conditions that cause the ventricular folds to oscillate or interact with the true vocal fold oscillations can reveal the effects of this supraglottic structure, which may be detrimental or facilitatory to true vocal fold vibration and the corresponding laryngeal acoustic output.

The model used in the present report is an extension of the work by Alipour *et al.*³ that presented a detailed description of a continuum model of vocal fold vibration, including a finite-element formulation and its validation. The extension to the model here is the inclusion of the ventricles and false vocal folds, a modification of the thyroarytenoid muscle distribution with extension into the lateral portion of the ventricular folds, and an update of the tissue properties (please refer to Table 1). The model includes three components: tissue mechanics, laryngeal aerodynamics, and vocal-tract acoustics (please refer to block diagram in Figure 1). Tissue mechanics dictate the potential for vibration of the TVFs and provide the geometry of the TVFs and glottis, displacements, and stress-strain distributions within the TVFs at every instant of time. The laryngeal aerodynamics calculates pressure and velocity fields throughout the larynx and the estimation of the external forces on the TVF surfaces. Vocal tract acoustics estimate the acoustic pressure field within the vocal tract and radiation from the mouth, nose, and skin surface. These three components can sometimes work independently, but generally need to work simultaneously. The model was shown to have stable self-oscillation for a wide range of lung pressures. Later, this model was used in the computational study of the effects of vocal fold bulging on phonation.⁴ However, the vocal fold model has partial contact and does not completely close due to the air flow modeling requirement and this may pose some limitation on application of the model.

Agarwal *et al.*⁵ showed that the FVFs may act to increase or decrease the flow resistance through the larynx depending upon the ratio of the FVF gap to the minimal glottal diameter. Others have also shown similar effects.^{6–9} The pressure distributions within the larynx have also been altered by the presence of the FVFs.^{5–7} Vibration of the FVFs can induce irregularity into the acoustic output.¹⁰ The FVFs may also obstruct the initiation of the downstream vortex¹¹ or create rebound vortices.¹² The presence of the FVFs may increase the amplitude of motion of the TVFs.⁹

METHODS

Vibration modeling

In the model, the vocal fold motion is defined by a two-dimensional displacement vector that is continuously distributed throughout the vocal folds. A planar oscillatory motion is assumed for the vocal folds (in the coronal plane). The TVFs and the FVFs are divided into 15 thin coronal layers. Because the layers are thin, the displacement field may be assumed to be uniform across the thickness of each layer. The mesh design is shown in Figure 2, where each layer is discretized into 84 triangular elements in the TVF and 20 triangular elements in the FVF. The TVF tissue included the body (TA muscle), the cover (minus the ligament), and the ligament, and the FVF had two tissues, a body (that is, the lateral superior portion of the TA muscle) and a cover, each with separate mechanical properties. At every time step (50 microseconds), the pressure distribution from the airflow was obtained and used to calculate the forcing vectors. Once the solution was found for the displacement of the vocal folds, the boundary conditions were enforced by looking at the nodal degrees of freedom. The nodes that were stationary or fixed were excluded from the solution scheme after the assembly process. Whenever the nodes on the medial surface of the vocal fold approached the corresponding nodes on the other side, a distance test was performed to see if it was less than a small value (0.001 cm). When this happened a soft impact with a small amount of penetration was applied and nodal displacements were updated accordingly. When the vocal folds touched each other, the contact nodes lose one degree of freedom. In other words, there may be complete contact and closure in some layers, but not all layers. Finally, the nodal coordinates were updated for that time step. Please refer to Alipour *et al.*³ for further details.

Air flow modeling

The airflow model is essentially the same as that described in Alipour *et al.*¹³ with increased grid resolution. The flow domain included a portion of the trachea (13 cm), the glottis and the ventricular gap (1.6 cm), and a supraglottal duct (22 cm). The flow domain was assumed to be two-dimensional and symmetric across the midline, and thus asymmetric flow fields were not studied here. A non-uniform rectangular grid (150 grid points along the channel, X, and 80 grid points across the channel, Y) was selected such that regions of higher velocities and larger pressure gradients contained more grid points. Since the glottal gap continually changes during each cycle of oscillation, a logarithmic distribution of grids was designed to ensure that there was the presence of a number of grid points in the region near closure. The glottis that was used in the two-dimensional flow was calculated by averaging the glottal gap in the longitudinal direction (along the vocal fold length).

It should be pointed out that two kinds of flow will be presented. One is the volume flow (mL/s), also called the glottal flow, that is most commonly known, discussed, taught, and related to glottal motion and source acoustics. The other is air velocity (cm/s), indicating how fast the air particles are traveling within the laryngeal airway. Indeed, the glottal flow is made up of the addition of the many air velocities across any glottal cross section at any given time. Here the choice of air velocity that will be shown is taken from the centerline of the glottal duct. It will become obvious that the glottal flow is a much simpler appearing signal than the centerline air velocity.

Acoustics of the vocal tract

The vocal tract pressures and flows were simulated with a one-dimensional wave-reflection method. In this method the vocal tract walls are assumed to be rigid and the acoustic pressures and acoustic velocities are related through the wave equation. By dividing the vocal tract (including the subglottal, pharynx, and mouth regions) into multiple cylindrical ducts of equal length (1 cm) with cross-sectional areas that were obtained for the vowel (such as /a/), one can estimate the pressure and velocity at every section. In this model the trachea had 18 sections, the pharynx had 10 sections, and the mouth had 12 sections. The pressure propagation at each junction of the two sections was subjected to reflection and attenuation. These pressures were calculated by a finite difference method. The details of the vocal tract modeling can be found in Titze.¹⁴

Transition between models

As shown in the block diagram of Figure 1, the components of the model are not independent and interface with each other through data sharing in FORTRAN common blocks. Some simplifying assumptions help to interface the 3D tissue mechanics, the 2D flow model, and the 1D acoustics. The forces on the vocal folds are defined by the pressure distributions that are provided from the flow model. Here the pressure distribution is 2D, and thus the tissue model accepts the 2D calculated pressure and applies it to the 3D cross section. The glottal geometry is converted to 2D for the flow calculation by preserving the cross sectional area, like converting a triangle to rectangle with the same height and same area. The 1D acoustic model is excited with the glottal volume flow which is calculated from the transglottal pressure and cross sectional area at the minimum glottal gap. The acoustic pressure is then used to update the transglottal pressure.

RESULTS

Figure 3 shows four waveforms simulated by the model. The simulation shown is for a lung pressure of 10 cm H₂O and elastic properties that are given in Table 1. The fundamental frequency was 171.8 Hz. The top trace is the subglottal pressure (Ps) signal, with an average value of 9.5 cm H₂O. The variations in the pressure correspond mainly to the first subglottal formant frequency of approximately 515 Hz (for a simulated uniform open-closed duct). The trace just below the subglottal pressure is the glottal volume velocity, also called the glottal flow (Ug), with an average value of 191 mL/s and a peak flow of about 400 mL/s. The third trace is the (maximum projected) glottal width (Gw) (as seen from above the glottis) calculated between the two TVFs, with a peak value of 1.63 mm. The maximum glottal

width is somewhat triangular in shape, but with some asymmetry. The glottal flow is skewed to the right, as expected. The glottal width is more triangular, as expected. The fourth trace is the (maximum projected) FVF gap (V_w) (seen from above the FVFs) calculated between the two FVFs with an amplitude of about 0.04 mm, indicating very small vibrations. All of these waveforms are in reasonable ranges when compared with experimental observations on human subjects. Figure 4 shows one cycle of the phonation indicated in Figure 3, showing the subglottal pressure, glottal flow, and glottal width. The skewing of the glottal flow is evident. This is seen by noticing that the point labeled 9 for the flow (U_g) at the height of the flow signal comes after the maximum glottal width (G_w) value near the time of 3 ms. Also, Figure 4 shows the subglottal pressure (P_s) rising near the glottal flow shut off near the time of 5 ms. This is due to the vocal folds coming together and impounding air pressure subglottally due to the momentum of the air coming from the “lung”. That is, the rise in subglottal pressure near flow shut off is a result of glottal closing and closure, as shown by the G_w value near the baseline. The numbered filled circles refer to chosen phases of the cycle (frames), the results for which will be discussed below.

To examine time dependent velocity and pressure distributions in the glottal region in time and space, five frames of the cycle in Figure 4 were selected as shown in Figure 5 with their coronal contours. Frames 3 and 5 are during opening of the glottis when the glottis is convergent, frame 7 is later in the cycle when the glottis is near maximally open with a shape that is slightly divergent (6 degree), and frames 9 and 11 are during closing of the glottis when the glottis is divergent. The numbers in the legend refer to the frame numbers shown in Figure 4. These glottal shapes are typical in phonation. That is, the glottis is convergent during glottal opening, and divergent during glottal closing. The model easily shows this typical behavior. Motion of the FVFs is also shown, but because the most medial portion is at a nominal (typical) location, large motions are not expected, as is also the case in normal human phonation.

Figure 5 shows that the glottis proper extends from approximately 14.3 to 14.8 cm and the ventricle with FVFs from 14.8 to 15.25 cm.

Figure 6 shows the streamlines of frames 5 and 9 with details of the vortical structure during opening (top graph) and closing (bottom graph). During each cycle, the glottal channel takes on converging, nearly rectangular, and diverging shapes during which a vortex is generated in the ventricle and grows and moves downstream. When the glottis is opening, the glottal shape is convergent and flow separates from the superior tip of the vocal fold. There is a vortex appearing medial (“above” in the figure) to the ventricular fold that rotates clockwise, and another vortex just past the vocal fold rotating counter clockwise. In contrast, a model without the ventricular folds (not shown here) exhibits only one large vortex downstream of the vocal folds. In the bottom graph during glottal closing, the glottis is divergent and flow separates within the glottis. There is a large vortex downstream of the glottis that rotates clockwise with some air flowing towards the ventricle. It should be noted that the vortex structure in a 3D model can be different from that in the 2D flow model that is presented here, and this could pose a pedagogical limitation of the model.

Centerline velocity distributions from the previous frames are plotted in Figure 7. As the glottis changes size and shape during the cycle, the air speed within the glottis also changes. Examination of the centerline velocities through the larynx suggests that they are dependent upon three factors, (1) glottal width, (2) glottal angle, and (3) the location of the downstream vortex. For **frame 3**, the glottal width is narrow and the glottal angle highly convergent. The corresponding centerline velocity increases throughout the glottis due to the convergence, then decreases throughout the ventricle-FVF region where the cross-sectional area is larger (Figure 5), and then quickly decreases past the FVFs where the cross-sectional area is largest (Figure 6).

For **frame 5**, the glottis is less convergent and more open than in frame 3, since the glottis is opening. Here the centerline velocity again increases throughout the glottis proper (due to the convergence), but then decreases more slowly through the ventricle-FVF region, and continues to gradually reduce in velocity up to approximately the axial location of the center of the vortex, at which point it then quickly decreases. Because the vortex is near the centerline, it tends to hold the centerline velocity to higher values until just past its center, at which point the centerline velocity drops rapidly. This is also the case for frames 7, 9, and 11.

For **frame 9**, the glottis is narrower and strongly divergent, with a maximum centerline velocity at the minimal glottal width, a decrease in centerline velocity past that point, further decrease through the ventricle-FVF region, and then continued decrease downstream but with a noticeable local increase at the axial distance at the center of the vortex, followed by a rapid fall off.

Frame 11 also shows unique features for its centerline velocity. The glottis is quite narrow with a highly divergent angle, reflecting the nearly closed glottis during glottal closing. The centerline velocity reaches a peak at the narrowest location, followed by a rapid decrease due to the low volume velocity and divergence angle, and then followed interestingly by a strong increase throughout the ventricle-FVF region and beyond, reaching a maximum at an axial location within the broad gradient of the vortex. The centerline velocity then reduces and exhibits a slight knee in its curve at the axial location of the center of the vortex still remaining in the duct.

When the FVFs are excluded, the velocity distributions in the model (not shown here) exhibit differences during closing (when the glottis has divergent shapes). During glottal closing the centerline velocity maintains high values for at least 4–5 times the thickness of the vocal folds before it diminishes.

Thus, the centerline velocities tend to (a) increase within the glottis when the glottis is convergent, (b) exhibit an increase and then a decrease within the glottis when it is divergent (with the maximum velocity at the minimum width), (c) decrease throughout the ventricle-FVF region (for the nominal FVF gap of 5.5 mm used here) except when the glottis is relatively wide open with a small glottal divergence angle, and (d) either fall (for convergent glottal shapes) or rise (for divergent glottal shapes, with exceptions) being conditioned by a convecting vortical structure near the centerline of the duct; the centerline velocity rapidly

falls when it reaches the axial location of the center of the vortex. The centerline velocity variations are thus indications of both geometric variations and the presence of vortical structures of the flow as they travel away from the glottis.^{15, 16}

The corresponding centerline pressure distributions are shown in Figure 8. During initial opening (**frame 3**), pressure is high within the glottis (which acts to push the vocal folds away from each other) and then decreases rapidly near the glottal exit due to the convergence angle, and curiously stays slightly negative until past the FVFs, showing a slight dip at the exit of the FVF region. The centerline pressure distribution for **frame 5** (slightly later in the glottal opening) is lower in value within the glottis and less steep near the glottis exit due to the less steep convergence angle and larger glottal width, and goes directly to near zero pressure at the exit of the glottis proper (not being influenced by the ventricle-FVF region). In **frame 7** the glottis is widest with relatively high flow. The transglottal pressure (seen as the intercept of the pressure trace with the Y-axis) at this time is relatively low (indicating the least flow resistance of the cases) and the centerline pressure drop is very gradual within the glottis, despite the 6 degree divergence.

During closing of the glottis (**frames 9 and 11**), the transglottal pressures are larger than for the other conditions of the cycle, and have steep drops to negative pressures essentially at and near the maximum glottal constrictions (negative pressures in the glottis act to help pull the vocal folds back toward each other), followed by pressure recovery (i.e., pressure increase) within the glottis. Frame 11 with the narrower width and greater divergence has a faster centerline pressure recovery (pressure increase) within the glottis.

An examination of the centerline pressure during the glottal opening of **frame 3** in the model when the FVFs are excluded (not shown here) suggests a much higher transglottal pressure, indicating the potential positive effects of the FVFs on the ease of vocal fold oscillation. Also, during closing such a model lacks the negative pressure for **frame 9**.

The simultaneous temporal variations of the centerline velocity at x grid numbers 55, 65, and 75 at x-location values of 14.65, 14.90, and 15.16 cm (please refer to Figure 5), are shown in Figure 9. These locations correspond to about one-third of the glottal length from the glottal exit, within the laryngeal ventricle, and in line with the FVF gap. There is a similarity among the velocity waveforms at the three locations; the gross changes are similar, with a prominent positive peak just before glottal closure when transglottal pressure rises and the glottal opening decreases, and a prominent lowest peak when the glottis is smallest. The overall average velocity is shown to be about 25 m/s. The minor variations at the 65 and 75 grid locations (in the ventricle and in the FVF gap) appear to be caused by movement of the vortical structure away from the glottis.

Finally, Figure 10 shows the FFT spectrum of the radiated sounds simulated by the model for the vowels /a/ and /i/. The formant structures of the vowels can be observed from the spectra. These spectra indicate that the model performs well in relating a glottal source and vocal tract to provide highly human appearing vowel spectra.

DISCUSSION

Vocal fold motion

Figure 5 shows the 5 phases of glottal wall motion studied here. The glottis shows expected behavior – convergent glottal shaping during glottal opening and divergent shaping during glottal closing. The glottal angles ranged from 42 degrees convergent to 54 degrees divergent. Thus, the elements of a robust mucosal wave were present. The three dimensionality of the vocal fold motion was observed from motion of the layers but is not shown here.

The effective glottal duct length (inferior to superior) was longest during glottal opening (approximately 0.4 cm during the convergent glottal shaping) and shortest during glottal closing (approximately 0.3 cm during divergent glottal shaping), a point important for calculating total force on the glottal walls. The contour of the vocal fold had a broad radius at glottal entry, thus preventing any *vena contracta*, but had rather sharp exit corners, which would drive intraglottal pressures closer to the exit than if it were well rounded.¹⁷ The maximum amplitude of motion of the vocal folds was approximately 1.6 mm, which appears to be within normal limits for vocal fold oscillation.

Velocity distributions

The centerline velocities were dependent upon three factors, the glottal width, glottal angle, and the location of the downstream vortex. The velocity increased as expected throughout a convergent glottis, and tended to decrease throughout a divergent glottis, and decreased past the true vocal folds when within the ventricle-FVF region. However, quite interestingly, the centerline velocity was highly dependent upon the location of the vortical structure that was produced at the exit of the glottis and was convected downstream. As seen in Figure 7, the shape of the centerline axial velocity distribution appears short for convergent glottal shapes but longer for divergent shapes. The relative acoustic effect of these dynamic changes needs to be investigated. It is expected that more detailed vortex structure would be achieved using higher densities of flow mesh at the cost of more computational time.

Pressure distributions

The basic shape of the dynamic pressure distributions shown in Figure 8 are expected if they follow behavior consistent with static configurations. That is, the results for the convergent glottal shape conditions have relatively high pressure values within the glottis with the highest pressure at the entrance to the glottis, then decreasing in pressure throughout the glottis until the end of the glottis where the pressure rapidly becomes atmospheric pressure (with some variation as mentioned above). The divergent cases tend to show a pressure dip near the minimum constriction area, which is typical¹⁸, although the dip is absent for the largest opening, 6 degree divergent case. The transglottal pressure (seen essentially on the y-axis in Figure 8) also is consistent with expectation, with higher values during glottal closing (because the momentum of the air moving toward the closing glottis will “crowd” the air together, creating compression and higher values), and lower values during glottal opening, and the lowest value for the most open condition.

The negative pressure in the divergent glottis is consistent with the simulation results of Mihaescu et al.¹⁶, where they computed unsteady flow and vortex structures in a static divergent glottis with a large eddy simulation method. They attributed the negative pressure to Bernoulli effects, flow structures, and vortices. The glottal jet exits and continues over the ventricle as a vortex is generated downstream of the glottis and grows and moves further downstream. This suggests that the presence of the FVF-ventricle acts to smooth and extend the glottal jet beyond the ventricle. However, due to lack of great resolution in this study, the detailed vortex generation and their movement into the ventricle as seen in Zheng et al.⁹ and Farahani et al.¹² was not achieved here.

CONCLUSIONS

This report is a demonstration study of an enhanced dynamic computational model, an extension of the “biophysical model” reported earlier.^{3, 4, 13} This is the first report of time-dependent pressure distributions and velocity distributions using this model. The model is used both as a verification of the extended model to produce realistic vocal fold motion, velocities, flows, and pressures, and as an instructive tool to show the interactions among these variables. The motion of the vocal folds is three dimensional, but the calculation of the aerodynamics is two dimensional in this model in that, at every time update, the glottal area is averaged along the glottal length to provide the equivalent glottal diameter over which the pressures are calculated and then applied back onto the medial surfaces of the vocal folds. It was found that:

1. The model is robust in that it easily can generate any length of time of computation with consistent cycles.
2. The motion of the vocal folds shows expected modes of vibration, including anterior-posterior and vertical motion (not shown here), but primarily transverse motion (shown here). The motion also indicates realistic changes between convergent and divergent glottal shaping.
3. Signals of subglottal pressure, glottal volume flow, and glottal width all appear realistic, including flow skewing. The fundamental frequency of 171.8 Hz and a primary subglottal resonance of approximately 515 Hz (not shown) also are realistic.
4. Pressure distributions for dynamically changing glottal configurations throughout the cycle appear to be reasonable in shape and size, and are consistent with constant flow modeling within model M5.¹⁷
5. The centerline velocity increased as expected throughout the convergent glottis, and tended to decrease throughout the divergent glottis, and decreased past the true vocal folds when within the ventricle-FVF region. The centerline velocity was highly dependent upon the location of the vortex structure produced at the exit of the glottis and convected downstream.
6. The false vocal folds did not vibrate significantly for the settings in this study, but the ventricle-FVF region affected the pressures downstream of the glottis by appearing to retain intraglottal pressures over a greater distance rather than

allowing the pressures to go directly to atmospheric values just past the glottis. There may have been a significant effect on the pressures and flows due to an interaction between the vortex and false vocal fold, given that the size of the vortex approximated the false vocal fold gap.

7. The acoustic output for /a/ and /i/ appear highly realistic, suggesting the usefulness of the model in demonstrating full phonatory behavior.

Such a model as the one used here can be used to create a wider range of phonatory situations to examine the numerous dependent variables such as flows, glottal angles, velocities, and acoustics, by controlling the independent variables such as adduction, lung pressure, closeness of the FVFs, and specific shapes of the vocal tract. By doing so, not only may new discoveries be possible relative to what creates what kinds of sounds (and their perceptions), but also contribute to educating practitioners regarding insights relevant to training and clinical care.

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Figure 1.
Block diagram of the model.

nap3, frame=1, Layer=1

Figure 2.
Finite element mesh in a coronal layer, including body (TA muscle), ligament, cover, and false vocal fold.

Figure 3.

Typical glottal waveforms, including (from top to bottom) subglottal pressure, glottal volume flow, maximum glottal width, and maximum false vocal fold width.

Figure 4.

One cycle of phonation for the first three signals of from figure 3. The filled circles refer to frames chosen for detailed analysis (see text). The frames are 0.5 ms apart.

Figure 5.

Five selected frames of a portion of the vocal fold wall contours, obtained by averaging along the anterior-posterior direction of the glottis. The numbers in the key correspond to the times shown in Figure 4.

Figure 6.
Detailed streamlines for frames 5 (top graph) and 9 (bottom graph) during glottal opening and closing.

Figure 7.
Centerline velocity values along the axial distance for the five selected frames.

Figure 8. Centerline pressure distributions along the axial distance for the five selected frames.

Figure 9. Three cycles of centerline velocity waveforms at three grid locations of 55, 65, and 75, corresponding to axial locations within the glottis, ventricle, and false vocal fold gap.

Figure 10.
FFT spectrum of simulated radiated sounds of vowels /a/ and /i/.

Table 1

Input parameters used in the model

Vocal folds static length	1.6 cm
Vocal folds lateral depth	1.0 cm
Vocal folds thickness	0.45 cm
Inferior glottal width	0.06 cm
Superior glottal width	0.02 cm
Lung pressure	1.0 kPa
Body Longitudinal Young's modulus	20 kPa
Cover Longitudinal Young's modulus	15 kPa
Ligament Longitudinal Young's modulus	30 kPa
Ventricular fold Longitudinal Young's modulus	10 kPa
Body Transverse Young's modulus	2 kPa
Cover Transverse Young's modulus	1.5 kPa
Ligament Transverse Young's modulus	3 kPa
Ventricular fold Transverse Young's modulus	1 kPa
Body Longitudinal shear modulus	12 kPa
Cover Longitudinal shear modulus	11 kPa
Ligament Longitudinal shear modulus	20 kPa
Ventricular fold Longitudinal shear modulus	10 kPa
Longitudinal Poisson's ratio for all tissue layers	0.4
Transverse Poisson's ratio for all tissue layers	0.9
Body viscosity	6 Poise
Cover viscosity	3 poise
Ligament viscosity	5 poise
Ventricular fold viscosity	3 Poise