Study of spatiotemporal liquid dynamics in a vibrating vocal fold by using a self-oscillating poroelastic model

Austin Scholp,¹ Caroline Jeddelloh,¹ Chao Tao,^{2,a)} Xiaojun Liu,^{3,b)} Seth H. Dailey,¹ and Jack J. Jiang¹

¹Department of Surgery, Division of Otolaryngology - Head & Neck Surgery, University of Wisconsin Medical School of Medicine and Public Health, Madison, Wisconsin 53792-7375, USA

²Shenzhen Research Institute of Nanjing University, Shenzhen 51800, China

³MOE Key Laboratory of Modern Acoustics, Nanjing University, Nanjing 210093, China

ABSTRACT:

The main purpose of this study is to investigate the spatiotemporal interstitial fluid dynamics in a vibrating vocal fold. A self-oscillating poroelastic model is proposed to study the liquid dynamics in the vibrating vocal folds by treating the vocal fold tissue as a transversally isotropic, fluid-saturated, porous material. Rich spatiotemporal liquid dynamics have been found. Specifically, in the vertical direction, the liquid is transported from the inferior side to the superior side due to the propagation of the mucosal wave. In the longitudinal direction, the liquid accumulates at the anterior-posterior midpoint. However, the contact between the two vocal folds forces the accumulated liquid out laterally in a very short time span. These findings could be helpful for exploring etiology of some laryngeal pathologies, optimizing laryngeal disease treatment, and understanding hemodynamics in the vocal folds.

© 2020 Acoustical Society of America. <https://doi.org/10.1121/10.0002163>

(Received 13 November 2019; revised 17 September 2020; accepted 21 September 2020; published online 19 October 2020)

[Editor: Zhaoyan Zhang]

Pages: 2161–2172

I. INTRODUCTION

Knowledge of vocal fold vibration not only gives an insight into voice production, but also provides important information about the development of laryngeal pathology. Computer models provide researchers with an effective tool to gain extensive insight about the vocal fold vibration involved in voice production since the parameters and configurations of these models can be easily defined and manipulated.

A good vocal fold model should be simple enough to allow conceptualization of the movement process, but also complete enough to demonstrate the intricate vibratory phenomena. Additionally, the computational cost of the model should be balanced with accuracy. A good balance of simplicity and completeness is achieved when the vocal folds are modeled as a continuous elastic solid.^{1–4} Elastic models are elegant in the way that they describe wave propagation in vocal fold tissue and conceptualize the production of the vocal fold self-oscillation during phonation. For this reason, they have been widely used to explore vocal fold collision,^{5,6} abduction and adduction,⁴ biphonation,⁶ vibration mode,⁷ energy transfer during phonation,⁸ irregular voice,⁹ ranking model parameters,¹⁰ parameter estimation,¹¹ and many other vocal phenomena.

However, the elastic model ignores one important characteristic of biological tissue: its biphasic nature. Vocal fold tissue is not an elastic solid, but a porous, elastic frame composed of specialized proteins, carbohydrates, lipids, collagen

fibers, and elastin fibers filled with interstitial fluid.¹² Because of the biphasic nature of vocal fold tissue, the ability of the elastic model to explain phenomena related to the fluid properties of the tissue is quite limited.

In order to overcome the shortcomings of elastic models, the poroelastic theory^{13–15} has been employed to describe various biological tissue characteristics, including those of human cancellous bone, lumbar discs, vesicles, cartilage, and tendons, among others. In these studies, the biological tissues are modeled as a composite of an elastic, porous solid with fluid occupying the pores. The properties of the tissues are governed by the porous solid, the fluid, and their interaction. These studies significantly improve our knowledge of the mechanical properties and microstructures of biological tissues. The poroelastic theory has also been used to describe the viscoelastic behavior of vocal fold tissue,¹⁶ the liquid redistribution in the vocal folds during phonation,^{17,18} and the normal model of the vocal folds vibration.¹⁹ Recently, Bhattacharya and Siegmund^{20,21} developed a high-fidelity numerical model, taking into account the tissue viscoelastic properties derived from biphasic theory. By estimating fluid movement from the hydrostatic stress gradient, they revealed that vibration and collision of the vocal folds will change the state of hydration within the tissue.²⁰ They also compared the fluid flow characteristics in the vocal folds for a range of phonation conditions and found that interstitial fluid displacement is heterogeneous and strongly dependent on the phonation condition.²¹ Erath *et al.*²² described viscoelasticity of vocal fold tissue using a modified Kelvin–Voigt configuration consisting of elastic and viscous elements in parallel. They found that the maximum interstitial fluid pressure generally

^{a)}Electronic mail: taochao@nju.edu.cn

^{b)}ORCID: 0000-0002-7826-9742.

increases with decreasing viscous dissipation and tissue elasticity. An interesting finding is that a global minimum in the total contact stress corresponds to physiologically reasonable tissue elasticity and fluid damping. Furthermore, Wu and Zhang²³ proposed a three-dimensional (3D) poroelastic model, considering water resupply, water movement within the tissue, water exchange through the epithelium, and surface fluid accumulation and discharge. They revealed that the dehydration generally increased with vibration amplitude, epithelial permeability, and reduced water resupply; moreover, the distribution of water loss within the vocal folds was non-uniform. Therefore, the poroelastic theory has shown great potential to describe the vocal fold vibration. However, it still lacks a self-oscillating vocal fold model that accounts for contact and possesses a biphasic material formulation.

In comparison to the elastic model where the main focus is on the mechanical properties (impact force, stress, and strain) of the vocal fold tissue during phonation,^{24–28} the current study will investigate the spatiotemporal interstitial fluid dynamics in a vibrating vocal fold. In order to further understand the biphasic nature of vocal fold tissue, we developed a self-oscillating poroelastic model of the vocal folds comprised of hydrated tissue. The poroelastic theory describes the dynamic behavior of the fluid component of vocal tissue and its interaction with the solid matrix. In comparison to the previous models, which did not consider the vocal fold contact,^{18,19} ignored the solid-fluid interaction stress from the solid equations,^{20,21} or imposed a time varying air pressure instead of a self-oscillating model,²³ this current model accounts for liquid-solid interaction, liquid movement, vocal fold contact, air pressure distribution obeying Bernoulli's law, and the flow-induced vocal fold self-vibration. Therefore, this model allows us to investigate the liquid movement in three directions and explores the effect of vocal fold contact on the liquid dynamics in vibrating vocal folds. This theory is briefly introduced in Sec. II. We employ the model to study the 3D fluid flow in a vibrating vocal fold in Sec. III. Finally, we discuss the potential contribution of the observed liquid dynamics to laryngeal physiology and phonation and draw conclusions in Sec. IV.

II. MODEL DEVELOPMENT

The current study uses a vocal fold model based on the poroelastic theory.¹⁷ The vocal fold is approximately represented by a rectangular parallelepiped with thickness (T) 0.4 cm, depth (D) 1.0 cm, and length (L) 1.6 (cm), where the lateral, anterior-posterior (AP), and inferior-superior distances are defined in x , y , and z coordinates, respectively, as shown in Fig. 1. This rectangular model has been used in previous studies concerning vocal fold vibration.^{7,17,29,30} These works have demonstrated that the rectangular model can accurately describe the basic behaviors of vocal fold vibration, such as the self-oscillation, eigen-mode and eigen-frequencies, mucosal wave propagation, and so on.

FIG. 1. (Color online) A diagram of the vocal fold model, where T , D , and L represent the thickness, depth, and length of the vocal fold, respectively. The fixed boundary condition was applied on the gray surfaces (the anterior surface, the posterior surface, and the lateral surface). The free boundary condition was applied on the top surface (x - y plane at $z=T$) and the bottom surface (x - y plane at $z=0$). A drive force based on Bernoulli's law was applied on the medial surface (the y - z plane at $x=0$) to generate the self-vibration of this model. The plane A, filled with a slash pattern, is located at the AP midpoint, where $y=0.8$ cm. The plane B, also filled with a slash pattern, is located at $x=0.1$ cm, which is just below the medial surface and represents one plane in the vocal cover.

A. The equation of motion

It is assumed that vocal fold tissue is transversally isotropic and follows the fluid-saturated porous tissue description.¹⁷ Moreover, for the sake of simplicity, it is assumed that the vocal folds are left-right symmetric about their midplane, there is no longitudinal strain of the poroelastic solid frame, and the amplitude of vocal fold vibration is small.

The zero longitudinal strain assumption is based on the actual biological situation of the vocal folds, where the vocal fold tissues have stronger stiffness in the longitudinal direction than in the transverse direction.³¹ Additionally, the glottal airflow pressure is perpendicularly applied on the surface of the focal folds. Therefore, it was found that the longitudinal movement is much smaller than the lateral and vertical movement.^{32–34} This assumption has also been verified by observations of the trajectories of vocal fold tissue flesh points during oscillation.^{32–34}

The motion of the vocal folds can be described by the following equations.^{13,14,17} The lateral (x -direction) movement of vocal-fold tissue satisfies

$$\rho_s \frac{\partial^2 u_x}{\partial t^2} + \gamma \frac{\partial u_x}{\partial t} - \pi_x = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z}, \quad (1)$$

$$\rho_f \frac{\partial^2 U_x}{\partial t^2} + \pi_x = \frac{\partial s}{\partial x}, \quad (2)$$

and the vertical (z -direction) movement satisfies

$$\rho_S \frac{\partial^2 u_z}{\partial t^2} + \gamma \frac{\partial u_z}{\partial t} - \pi_z = \frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}, \quad (3)$$

$$\rho_F \frac{\partial^2 U_z}{\partial t^2} + \pi_z = \frac{\partial s}{\partial z}. \quad (4)$$

The equation of motion in the y -direction includes only the liquid fraction because the longitudinal movement of the solid frame is ignored,

$$\rho_F \frac{\partial^2 U_y}{\partial t^2} + \pi_y = \frac{\partial s}{\partial y}. \quad (5)$$

In the above equations, U_i and u_i ($i=x, y, z$) are the displacements of the liquid and solid components in the i -direction, respectively; ρ_S and ρ_F represent the total solid mass and the total fluid mass in the fluid-solid aggregate per unit volume; γ is a damping constant related to the energy dissipation of solid frame that could result from friction between the tissue fibers; π_i ($i=x, y, z$) is the force (generated due to the solid-fluid interaction) acting on the solid and fluid components per unit volume in the i -direction; σ_{ij} ($i, j=x, y, z$) represent the normal ($i=j$) and shear ($i \neq j$) stresses acting on the solid per unit area in the i -direction; and s is the force applied on the fluid per unit area. Due to the small vibration assumption, the liquid mass change due to its movement in the tissue is small in comparison to its static mass. Our calculations show that the liquid strain is smaller than 10%, even for the vocal fold cover. Therefore, ρ_F is fixed in Eqs. (2), (4), and (5) for the small vibrations.

The forces σ_{ij} and s are generated due to the deformation of the fluid-solid aggregate. These stress components in the tissue can be linked to the liquid displacement (U_x, U_y , and U_z) and the solid displacement (u_x, u_y, u_z) by^{13,14}

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \\ s \end{bmatrix} = \begin{bmatrix} C & \lambda' & \lambda & 0 & 0 & 0 & Q \\ \lambda' & 0 & \lambda' & 0 & 0 & 0 & Q' \\ \lambda & \lambda' & C & 0 & 0 & 0 & Q \\ 0 & 0 & 0 & \mu' & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu' & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu & 0 \\ Q & Q' & Q & 0 & 0 & 0 & R \end{bmatrix} \begin{bmatrix} e_{xx} \\ 0 \\ e_{zz} \\ e_{xy} \\ e_{yz} \\ e_{zx} \\ \varepsilon \end{bmatrix}, \quad (6)$$

where $e_{ii} = \partial u_i / \partial i$ ($i=x, z$) and $e_{ij} = \partial u_i / \partial j + \partial u_j / \partial i$ ($i, j=x, y, z$; $i \neq j$) are the normal and the shear strain of solid; $\varepsilon = \partial U_x / \partial x + \partial U_y / \partial y + \partial U_z / \partial z$ is the strain of fluid; $C = \lambda + 2\mu$, where λ and μ are the Lamé constants in the x - z plane and λ' and μ' are the Lamé constants along the longitudinal fiber axis; R is a measure of the amount of water being forced into the cube element under a constant pressure; Q and Q' are coupling coefficients of the solid volume change and the fluid volume change.

For an isotropic material, π_i ($i=L, T$) can be related to the fluid-solid relative motion by¹³

$$\pi_{L,T} = \alpha_{L,T} \frac{\partial^2}{\partial t^2} (U_{L,T} - u_{L,T}) + \beta_{L,T} \frac{\partial}{\partial t} (U_{L,T} - u_{L,T}). \quad (7)$$

The subscript L represents the direction parallel to the longitudinal fiber in the vocal fold tissue, and the subscript T represents the direction perpendicular to the longitudinal fiber. Previous studies have shown that most fibers in the vocal fold are aligned longitudinally.³⁵ Therefore, the permeability of fluid is expected to be significantly higher in the longitudinal direction than in the other directions ($\alpha_L, \beta_L \ll \alpha_T, \beta_T$). Based on this factor and the assumption of a small vibration, we have

$$\pi_{x,z} \approx \alpha_T \frac{\partial^2}{\partial t^2} (U_{x,z} - u_{x,z}) + \beta_T \frac{\partial}{\partial t} (U_{x,z} - u_{x,z}). \quad (8)$$

When the vocal fold is vibrating, the longitudinal fiber is bent. In this situation, both the force parallel to the longitudinal fiber (π_L) and the force perpendicular to the longitudinal fiber (π_T) contribute to the force in the y -direction (π_y). For a small amplitude vibration, the y -component of π_L and π_T can be approximated as $\alpha_L \partial^2 U_y / \partial t^2 + \beta_L \partial U_y / \partial t$ and $\pi_x \partial u_x / \partial y + \pi_z \partial u_z / \partial y$. The force π_y is the resultant force of the following components:

$$\pi_y \approx \alpha_L \frac{\partial^2 U_y}{\partial t^2} + \beta_L \frac{\partial U_y}{\partial t} + \frac{\partial u_x}{\partial y} \pi_x + \frac{\partial u_z}{\partial y} \pi_z. \quad (9)$$

Paired with the above stress-strain relationship depicted in Eqs. (6)–(9), the equations of motion [Eqs. (1)–(5)] describe the solid and liquid displacements of the vocal fold tissue.

B. Boundary and initial conditions

Given the boundary and initial conditions, we can completely determine the displacement vectors of the solid frame and the liquid at any time by solving Eqs. (1)–(5).

The fixed boundary conditions (i.e., $u_i = U_i \equiv 0$, $i=x, y, z$) were applied on the anterior side (x - z plane at $y=0$), posterior side (x - z plane at $y=L$), and the lateral surface (y - z plane at $x=D$), as shown in Fig. 1(a) with the gray plane. The free boundary conditions were applied on the superior and inferior surfaces. Moreover, because the vocal fold mucosal covering consists of a stratified squamous epithelium and the liquid in the vocal folds cannot permeate and leak from the epithelium, it is assumed that there is no relative movement between liquid and solid in the boundary surface ($u_i = U_i$, $i=x, y, z$).

In order to generate the vocal fold oscillation, this study described the air pressure distribution according to Bernoulli's law and the effect of the flow separation is ignored. The drive force (P_{air}) can be calculated as

$$P_{air} = \begin{cases} 0 & (z \geq z_m) \\ P_s [1 - G^2(z_m)/G^2(z)]; & (z < z_m). \end{cases} \quad (10)$$

In Eq. (10), $G(z) = \int_{y=0}^{y=L} (u_0 + u_x(y, z)) dy$ represents the glottal area at position z . $u_x(y, z)$ is the lateral displacement of the medial surface node at (y, z) . z_m is the position where $G(z_m)$ reaches its minimum value [$G(z_m) \leq G(z)$ for $\forall z$]. P_s is the subglottal pressure. $u_0 = 0.05$ cm is the prephonatory glottal half-width. The driving force is applied to the medial surface. Since there is no relative movement between liquid and solid in the boundary surface, the liquid and solid in the surface were actually combined together. The force was transferred to the solid and liquid, simultaneously.

For normal phonation, the glottal airflow can be considered as an incompressible Newtonian laminar fluid. Airflow in the AP direction is weak. Moreover, the vibration of vocal fold is regular. Thus, the air pressure can be assumed to be constant in the AP direction.

The contact between the left and right vocal folds is also considered in the current model. Because of the assumption of left-right symmetry, the interaction between the vocal fold and a midplane ($x = -0.05$ cm) was used to represent the contact between one vocal fold and the opposing vocal fold.^{5,6} For any time integration interval from t to $t + \Delta t$, once the medial surface of the right vocal fold contacts or crosses the midplane [$u_0 + u_x(y, z) \leq 0$], impact occurs. The time t_c of collision is calculated. Then, the movement of the vocal folds is recalculated from t to $t + t_c$. Then, the movement of the vocal folds from $t + t_c$ to $t + \Delta t$, is also re-integrated by fixing the displacement at the contact point at $u_0 + u_x = 0$. The process is repeated within the left interval. The vocal folds are separated again and $u_0 + u_x(y, z) > 0$.

The initial displacements of all nodes are set to zero. Because the initial glottal pressure of a rectangular glottis is zero [see Eq. (10)], an initial velocity of 20 cm/s is applied to the nodes on the inferior half of the medial surface to start the vibration. The velocity of all the other nodes is initiated to zero. In this study, the model shape fits the Cartesian coordinate system well, and the finite difference scheme is an easy way to discretize and integrate the model Eqs. (1)–(5) and solve them numerically.¹⁷ The model is discretized with the spatial step sizes $\Delta x = 0.1$ cm, $\Delta y = 0.08$ cm, and $\Delta z = 0.04$ cm in the x , y , and z coordinates, respectively. The vibration of the vocal folds is predicted by integrating the model equations with a temporal step size $\Delta t = 50 \times 10^{-6}$ s. For such a small time-step (about 100–200 steps per cycle of the vocal fold vibration), the deformation of the solid and fluid is very small in each time-step. The fluid-solid interaction can thus be solved.

III. RESULTS AND DISCUSSION

Using the model proposed above, we studied the spatio-temporal characteristics of the liquid movement in a vibrating vocal fold. The model parameters used in this study are given in Table I and are the same as those used in a previous study of a poroelastic model.¹⁷ Here, the elastic parameters, such as μ and μ' , are measured from various vocal fold tissues^{36,37} and have been successfully used in the previous

TABLE I. The parameters used in the vocal fold model.

ρ_s	0.9 g/cm ³	λ	3.5 kPa
ρ_F	0.1 g/cm ³	γ	100.0 g/s·cm ³
μ'	20.0 kPa	$\beta_{x,z}$	440.0 g/s·cm ³
μ	0.50 kPa	β_y	100.0 g/s·cm ³
α_T	0.02 g/cm ³	R	0.20 kPa
α_L	0.00 g/cm ³	Q	0.15 kPa

elastic models. The total mass (solid + fluid) per unit volume is $0.9 \text{ g/cm}^3 + 0.1 \text{ g/cm}^3 = 1.0 \text{ g/cm}^3$, which is close to the density of the tissue.

For convenience, two cross-sections are defined, as shown in Fig. 1. The cross-section A is the transverse cross-section located at the AP midpoint ($y = 0.8$ cm). The cross-section B is located at $x = 0.1$ cm, which is just within the medial surface.

A. Validation of the self-oscillating poroelastic model

Before the proposed model is used to study the liquid dynamics in the vibrating vocal folds, the temporal pattern of glottal width and surface displacement of the vocal folds are given as the basic model output. Figure 2(a) illustrates the glottal width (G_w) as a function of time, where the lung pressure is $P_L = 0.8$ kPa (≈ 8 cmH₂O). The vocal fold collision significantly affects vibration. Due to the vocal fold contact, G_w is an approximately triangular wave form. During collision, the vocal folds contact at the midline of

FIG. 2. (Color online) Glottal width and the mucosal wave propagation with a subglottal pressure $P_s = 0.8$ kPa (≈ 8 cm H₂O). Here, we have removed an initial transient behavior with a length of 2 s to ensure purely cyclic behavior. (a) The wave form of the glottal width (G_w) between the two vocal folds. (b) The lateral displacement (u_x) of wave forms at the AP midpoint of the medial surface, where curves 1, 2, 3, 4, 5, 6, 7 correspond to nodes at $z = 1.2, 1.6, 2.0, 2.4, 2.8, 3.2,$ and 3.6 mm, respectively. In this figure, the three dotted lines correspond to $t = 4.5$ ms (before collision), $t = 6.0$ ms (in the process of collision), $t = 8.0$ ms (after collision).

the glottis, the glottis closes, and the glottal width is zero. When the glottis is completely open, the maximum glottal width is about 1.0 mm. The waveform and peak value of the glottal width agree with the excised larynx experiments and clinical observations using high speed video.^{34,38,39} Figure 2(b) presents the lateral displacement (u_x) of the solid tissue component at the AP midpoint of the medial surface. Curves 1–7 correspond to the position of nodes at varying inferior and superior distances, $z = 1.2$ – 3.6 mm. The displacement waveforms of the nodes at $z = 2.8$, 3.2 , and 3.6 mm (curves 5, 6, 7) are symmetrical and sinusoidal-like in shape because the collision is weak in this region. However, when contact occurs, clipping distortion appears because the impact compresses the vocal fold tissue. The waveforms at $z = 1.2$, 1.6 , 2.0 , and 2.4 mm (curves 1, 2, 3, 4) are deformed. Moreover, the u_x waveform on the inferior side is ahead of that near the superior position. This is because the mucosal wave propagates from the inferior side to the superior side along the medial surface of the vocal fold mucosa. It can be roughly estimated from Fig. 2(b) that the mucosal wave velocity is about 3.3 m/s, which is within the range of mucosal wave velocities measured in previous experiments.^{40–42} All these waveform characteristics, which are related to the vocal fold contact, are reasonable and agree with previous experimental observations^{34,38,39,41} and model simulations.^{3,28}

In addition to the temporal waveform, the continuous model can also provide spatial information about the vocal folds during phonation. Figure 3 presents the profiles of cross section A at three moments, where Figs. 3(a), 3(b), and 3(c) correspond to three time points: before collision ($t = 4.5$ ms), in the process of collision ($t = 6.0$ ms), and after collision ($t = 8.0$ ms), respectively. In this figure, the initial position of the medial surface is at $x = 0.0$ mm, and the initial half-glottal width is $u_0 = 0.05$ cm. The collision occurs when the displacement of the medial surface nodes reaches $x = -0.05$ cm.

As shown in Fig. 3(a), before collision, the inferior side is moving toward the left-right midplane. The glottis has a divergent shape due to the propagation of the mucosal wave. The airflow is accelerated, and the intraglottal pressure is decreased due to Bernoulli's effect. The low intraglottal pressure closes the glottis, and vocal fold collision occurs, as shown in Fig. 3(b). During the closing phase, the vocal folds make contact at the midline of the glottis, thus cutting off the airflow. The subglottal pressure (P_s) then pushes the vocal folds apart. After the glottis is opened, air escapes from the subglottis and the glottis has a convergent shape, as shown Fig. 3(c). At the same time, the intraglottal airflow pressure is decreased due to Bernoulli's effect as air flows at a high velocity through the glottis, which provides an aerodynamic driving force. This aerodynamic force and the elastic recoil of the deformed tissue cause the vocal folds to close again, and a new cycle begins, creating sustained oscillation of the vocal folds. The profiles given in Fig. 3 represent mucosal wave propagation and tissue deformation during phonation.

All the above results are reasonable when compared with previous numerical simulations³ and experimental

FIG. 3. The profiles of the cross section A at three moments during vocal fold vibration, where figures (a), (b), and (c) correspond to the moments before collision ($t = 4.5$ ms), in the process of collision ($t = 6.0$ ms), and after collision ($t = 8.0$ ms), respectively.

observations,⁴¹ providing a primary validation of the proposed poroelastic model.

B. Temporal pattern of the fluid movement in a vibrating vocal fold

Interstitial fluid movement is a useful output of the proposed poroelastic model, which cannot be predicted by other models. Figure 4 illustrates the temporal pattern of liquid movement at the AP midpoint of the vocal fold ($y = 0.8$ cm, $x = 0.1$ cm), where curves 1–7 correspond to the position of nodes at varying inferior and superior distances, $z = 1.2$ – 3.6 mm. In the lateral and vertical directions, the relative interstitial fluid displacements are defined as $\Delta U_x = U_x - u_x$ and $\Delta U_z = U_z - u_z$. However, due to the AP symmetry of the model, the liquid and solid displacements at the AP midpoint are always zero ($U_y = 0$, $u_y = 0$, $U_y - u_y = 0$). Therefore, we use the longitudinal liquid strain ($\epsilon_y = dU_x/dy$) to measure the longitudinal interstitial fluid movement near the AP midpoint. A positive fluid strain indicates that the fluid is squeezed out of the region, whereas a negative fluid strain means that the fluid is accumulated at the midpoint.

FIG. 4. (Color online) The waveform of the liquid component in a vibrating vocal fold. The curves 1–7 correspond to seven nodes at the AP midpoint of the subsurface B . Their coordinates are $(x, y, z) = (0.1, 0.8, z_i)$ cm, where $z_i = 1.2, 1.6, 2.0, 2.4, 2.8, 3.2$, and 3.6 with $i = 1-7$. (a) The relative displacement in the lateral direction, where $\Delta U_x = U_x - u_x$. (b) The longitudinal liquid strain ($\epsilon_y = dU_y/dy$), where a positive liquid strain indicates that the liquid is squeezed out, and a negative ϵ_y means there is liquid accumulation. (c) The relative displacement in the vertical direction, where $\Delta U_z = U_z - u_z$.

As shown in Fig. 4, during vibration of the vocal folds, the interstitial fluid is also vibrating within the tissue. In the lateral direction (x -direction), the waveform of fluid displacement is similar to that of the surface solid. However, comparing Fig. 4(a) with Fig. 2(b), we notice that the phase of fluid displacement is lagging behind the solid displacement due to inertial effects.

In the longitudinal direction (y -direction), excluding the fluid in the superior region, the longitudinal fluid strain is always negative. This result indicates that fluid is accumulated at the midpoint, and this corresponds well with experimental and modeling results from studies in which vocal fold collision was not considered.^{17,18,43} As shown in Fig. 4(b), the fluid strain in the region where the strongest collision happens (curves 2, 3, 4) increases suddenly during collision, which indicates that fluid is squeezed out of the midpoint region quickly. A similar phenomenon does not occur in the region where there is no collision (curves 5, 6, 7). Therefore, it can be concluded from these results that the abrupt fluid movement is induced by the vocal fold collision.

In the inferior-superior direction (z -direction), the relative fluid displacement at the inferior (curve 1) and superior (curves 5, 6, 7) sides are nearly 180 degrees out of phase. In the model, the collision happens at $z = 1.6, 2.0, 2.4$ mm (curves 2, 3, 4). The relative fluid displacement below the impact point is out of phase with those above the impact point. Therefore, it can be said that the collision breaks the phase of the fluid wave in the tissue.

C. Liquid movement in the transverse cross-section

During vocal fold vibration, the AP midpoint has the maximum vibratory amplitude and the strongest impact pressure.^{5,28} Insight into the liquid movement in this region is important in understanding the effects of the vocal fold collision on the interstitial fluid dynamics.

The displacement and velocity vectors of the interstitial fluid allow us to gain insight into the fluid movement and distribution in the vibrating vocal folds. Figures 5 and 6 present the relative fluid displacement and the relative fluid velocity at cross section A, where Figs. 5(a)–5(c) and Figs. 6(a)–6(c) correspond to the following time points: before collision ($t = 4.5$ ms); in the process of collision ($t = 6.0$ ms); and after collision ($t = 8.0$ ms). The arrows in the vocal fold

FIG. 5. (Color online) Relative fluid displacement on the cross-section A, where the arrows in the vocal fold profile represent the relative displacement vector $\Delta \mathbf{U} = \mathbf{U} - \mathbf{u}$. (a) The moment before collision ($t = 4.5$ ms). (b) The moment in the process of collision ($t = 6.0$ ms). (c) The moment after collision ($t = 8.0$ ms).

FIG. 6. (Color online) Relative fluid velocity in the cross-section A, where the arrows represent the relative velocity vector $\Delta \mathbf{V} = \mathbf{V} - \mathbf{v}$. (a) The moment before collision ($t = 4.5$ ms). (b) The moment in the process of collision ($t = 6.0$ ms). (c) The moment after collision ($t = 8.0$ ms).

profile represent the relative displacement vector $\Delta \mathbf{U} = \mathbf{U} - \mathbf{u}$ and the relative velocity vector $\Delta \mathbf{V} = \mathbf{V} - \mathbf{v}$. Clearly, the divergence and convergence of the relative displacement vectors indicate the loss and accumulation of fluid. The convergence of the relative velocity vector indicates that the fluid is flowing into this region, whereas the divergence of relative velocity vector denotes that the fluid is leaving the region. The profiles of the vocal folds at different moments are also plotted with the dotted lines in Figs. 5 and 6.

Figures 5(a) and 6(a) illustrate the situation before collision ($t = 4.5$ ms). In the lateral direction, the relative fluid displacement vectors, especially near the inferior lip, point to the depths of the vocal fold tissue, as shown in Fig. 5(a). The fluid content near the medial surface is lower during the closing phase of vibration than in the static vocal folds. This is because the fluid movement lags behind the solid movement due to inertial effects and because the inferior lip is drawn toward the midplane. However, the velocity vectors near the inferior lip are pointing in the direction opposite to the displacement vector in this region, as shown in Fig. 6(a). This indicates that the fluid is redistributing towards the surface of the vocal cover. The results of the fluid redistribution can be seen in the next moment, $t = 6.0$ ms, as shown in Fig. 5(b). In addition, in the vertical direction, the mucosal wave

is propagating from the inferior side to the superior side, and its peak is located at the inferior side of the vocal folds. The fluid near the peak of the mucosal wave is also moving in the same direction as the mucosal wave propagation, as shown in Fig. 6(a).

Figures 5(b) and 6(b) illustrate fluid velocity and displacement during collision ($t = 6.0$ ms). The peak of the mucosal wave propagates to about $z = 2.0$ mm of the medial surface of the vocal folds and the collision occurs there [Fig. 5(b)]. In the lateral direction, the collision significantly decreases the relative displacement vector length, as shown in Fig. 5(b). The shortest vector length appears at the collision region ($z = 1.6$ – 2.4 mm). Simultaneously, the velocity vectors in this region are pointing toward the medial surface, and the longest vector appears here. These observations point to the conclusion that the fluid is still quickly redistributing into the vocal cover. This phenomenon could be explained as follows: vocal fold collision suddenly stops the movement of the medial surface. However, the interstitial fluid inside the tissue continues to move toward the left-right midplane due to inertia. Therefore, the lateral displacement of the fluid component is decreased relative to that before collision. Moreover, the most significant change of the relative fluid displacement happens around the collision region.

In the inferior-posterior direction, the velocity vectors below the collision region ($z < 2.0$ mm) are pointing to the superior lip [Fig. 6(b)]. The fluid is moving from the inferior lip to the superior lip with the propagation of the mucosal wave, which results in the fluid accumulation in the superior lip as shown in Fig. 5(c).

Finally, after collision, the peak of the mucosal wave propagates to the superior lip at $t = 8.0$ ms, as shown in Figs. 5(c) and 6(c). In the lateral direction, the displacement is small due to refilling of fluid. In the vertical direction, the fluid is accumulated at the superior lip of the vocal folds [Fig. 5(c)] because of the propagation of the mucosal wave. Additionally, the velocity vector near the superior lip is still pointing upward [Fig. 6(c)].

In summary, before vocal fold collision, vocal fold vibration causes the fluid content near the medial surface to decrease relative to the static situation because of the phase difference between the fluid and solid component displacements. During collision, the fluid content is redistributed to the medial surface, and the most significant fluid redistribution can be observed around the collision region. In addition, the fluid near the medial surface is squeezed from the inferior lip to the superior lip in the same direction as the mucosal wave propagation.

The fluid is observed to move in the same direction as the mucosal wave propagation. These results imply that the liquid could be carried from the inferior region to the superior region. It was commonly observed that mucus is usually aggregated on the superior edge in vocally normal speakers.⁴⁴ Moreover, by using a poroelastic model, Wu and Zhang²³ also found that an upward movement of water within the surface liquid layer along the medial surface results in a gradual water accumulation on the superior edge

of the vocal fold. The phenomenon revealed by our model is consistent with clinical observations and other model predictions.

Wu and Zhang²³ predicted instantaneous fluid movement inside the vocal fold over one oscillation cycle. They revealed a periodic fluid movement that was closely related to the imposed periodic vocal fold vibration. Bhattacharya and Siegmund²⁰ also found that hydrostatic stress periodically changes with vocal fold vibration. Before collision, the stress vectors point to the medial surface. However, when vocal collision occurs, the impact will cause the stress vectors to point in the opposite direction. According to Darcy's law, the liquid relative velocity is proportional to the gradient of hydrostatic stress. Our model predicts that when liquid is moving to the surface before collision, then the vocal fold contact pushes the liquid back [Fig. 5(c)]. The results of our model and the previous studies qualitatively agree with each other. Therefore, these agreements validate the current vocal fold model.

D. Liquid movement in the AP plane

The human vocal fold cover is composed of epithelial cells and the superficial layer of the lamina propria (also known as Reinke's space). The cover is very loose and abundant with interstitial fluid and proteins, which allows the cover to easily slide over the deeper layer of tissue.³¹ The vocal fold cover determines the viscoelastic characteristics of the vocal folds relevant to vocal fold vibration because it serves as the vibratory component in phonation. Furthermore, many vocal diseases, such as Reinke's edema, polyps, nodules, and scars, often appear in this layer. Knowledge of fluid dynamics in the vocal fold cover is important for understanding vocal fold vibration and vocal disease development.

Figures 7 and 8 illustrate the relative displacement vectors and the relative velocity vectors in the subsurface *B*. This plane (*B*) is located 0.1 cm below the medial surface, which corresponds to the cover of the true vocal folds, as shown in Fig. 1. In order to show the longitudinal fluid velocity clearly, the relative velocity components in the *y* and *z* directions are plotted with a scale factor of 10:1 in Fig. 8. In contrast to the solid component, longitudinal movement of the fluid component is included in the poroelastic model. Rich fluid dynamics in the *y* direction can be observed in the vocal cover, as shown in Figs. 7 and 8.

Before collision ($t = 4.5$ ms), the displacement vectors are pointing to the AP midpoint of the vocal folds as shown in Fig. 7(a), which suggests that the fluid accumulates at the AP midpoint. At the same time, the velocity vectors at the anterior and posterior edges have the maximum length and are pointing to the AP midpoint, as shown in Fig. 8(a). This demonstrates that the fluid is moving toward the midpoint. These results agree with the previous simulations, analytic results, and experimental measurements.^{17,18,43} In addition, the largest liquid accumulation appears at the AP midpoint of the inferior lip, which is where the peak of the mucosal wave reaches at this time point.

FIG. 7. (Color online) Relative liquid displacement in the cross-section *B*. (a) The moment before collision ($t = 4.5$ ms). (b) The moment in the process of collision ($t = 6.0$ ms). (c) The moment after collision ($t = 8.0$ ms).

At time $t = 6.0$ ms, the peak of the mucosal wave is located at about $z = 2.0$ mm and collision occurs at this location [the solid line box in Figs. 7(b) and 8(b)]. The relative displacement vectors converge at the collision region, meaning the maximum level of fluid accumulation is located at the peak of the mucosal wave.

An interesting phenomenon of the fluid dynamics that should be noted in the phase of vocal fold collision is that

FIG. 8. (Color online) Relative liquid velocity in the cross-section *B*. (a) The moment before collision ($t = 4.5$ ms). (b) The moment in the process of collision ($t = 6.0$ ms). (c) The moment after collision ($t = 8.0$ ms).

the displacement vectors are convergent at the collision region [Fig. 7(b)]. However, the velocity vectors point to the opposite direction, and they are divergent at the same region, as shown in Fig. 8(b). In order to show the phenomenon more clearly, Fig. 9 shows the liquid acceleration in vibrating vocal folds. Figures 9(a) and 9(b) give the longitudinal liquid velocity and acceleration at a point near the midpoint and 0.1 cm below the medial surface. It is seen that the vocal fold collision generates a high peak in the waveform of velocity and acceleration. The accelerations during the collision are almost three times higher than those before or after collision. Figure 9(c) shows the liquid acceleration during collision ($t = 6.0$ ms). It is seen that all acceleration vectors point outwards from the collision region. This means that the fluid accumulated at the collision zone is quickly leaving the region. Furthermore, the velocity and acceleration vectors are longest around the collision, where the fluid is leaving the fastest. This phenomenon might be explained as being the result of the joint effects of both the mucosal wave propagation and the vocal fold collision. The collision occurs where the mucosal wave reaches its peak. The peak of mucosal wave causes the fluid accumulation as was discussed above. However, the strong impact squeezes the fluid out of this region in a very short duration.

Finally, Figs. 7(c) and 8(c) illustrate the displacement and velocity maps after collision. As a result of collision, the level of fluid accumulated at the AP midpoint is greatly decreased, shown by the relative displacement vectors in Fig. 7(c). Simultaneously, the relative velocity vector near the collision region is pointing to the AP midpoint, as shown in Fig. 8(c). The fluid begins accumulating toward the AP midpoint again.

FIG. 9. (Color online) Relative liquid acceleration in vibrating vocal folds. (a) The longitudinal liquid velocity, near the midpoint. Positive velocity represents the direction moving away from the midpoint. (b) The longitudinal liquid acceleration. Positive acceleration represents the direction moving away from the midpoint. (c) The relative liquid acceleration at the moment of collision ($t = 6.0$ ms).

E. Clinical relevance

The complex biphasic nature of the vocal folds plays an essential role in understanding the etiology of laryngeal pathologies. Knowledge of the interstitial fluid movement patterns can provide a prediction of the effects of vocal fold collision. The fluid moves with high velocity and acceleration immediately after vocal fold collision, signifying that the fluid could absorb some of the force of the impact. Future work with this model could explore the effects of limited fluid movement, thus limited force absorption, and its effects on lesion formation. In this way, this model could help pinpoint the etiology of laryngeal pathologies. This model could also help in understanding the treatment of some vocal fold pathologies. Further use of the model to study the fluid dynamics both before and after a vocal fold lesion, as well as before and after treatment for the lesion, could reveal new visuals for fluid dispersion before and after the recovery process, thus offering a new perspective on many treatments. In addition, this information could portray new information about the rupture and healing process of local blood vessels. For instance, as blood mixes with interstitial fluid following a vocal hemorrhage, the modeling of the fluid dynamics could show a new perspective on the bleeding and healing process. The further study of vocal cord lesions with this model could therefore influence the field of hemodynamics of the vocal folds. This poroelastic model has the capacity to modernize knowledge of disease treatment and hemodynamics, as well as strengthen the field of laryngeal etiology, and as such is a crucial tool for all physicians.

Two findings merit further discussion. One is that the fluid is transported from the inferior lip to the superior lip in the vertical direction, which is the same direction as the mucosal wave propagation. In order to more easily understand this phenomenon, we can consider the poroelastic model of vocal fold tissue as a rubber tube filled with water and consider mucosal wave propagation to be a tube deformation induced by a rolling process of external wheels, as shown in Fig. 10. The mucosal wave is propagated from the inferior side to the superior side, which is analogous to the wheels rolling along the rubber tube from the lower side to the upper side. We know that if the wheels roll over the rubber tube from the lower side to upper side, as shown in Fig. 10, the water in the tube will be squeezed in the same direction. The fluid motion in a vibrating vocal fold can be intuitively understood in a similar way.

The second finding is the sudden change of fluid distribution induced by the vocal fold collision. Before the collision, the fluid accumulates near the AP midpoint. However, the collision quickly pushes the accumulated fluid out of this region. In the time domain, it can be found that the process of fluid redistribution is extremely rapid because the collision has a short duration. This means that the velocity and acceleration of the fluid are high during this collision-induced fluid redistribution process. According to Newton's second law of motion, a large force is needed to generate a

FIG. 10. (Color online) Schematic drawing of the liquid transport induced by the mucosal wave propagation. (a) Stage 1, (b) stage 2, (c) stage 3.

high acceleration. Therefore, part of the impact functions to accelerate fluid movement, and the impact energy spreads out with the moving fluid. In other words, the moving fluid component in the vocal tissue could potentially absorb impact force. Based on this phenomenon, we can hypothesize that the fluid motion could be helpful in avoiding tissue damage caused by vocal fold collision via redistribution of the fluid to disperse the forces of collision. Clinically, it is also interesting to hypothesize that fluid distribution could become more impaired as the degree of pathology within the lamina propria increases, potentially setting into motion a feed-forward cycle. This same notion may apply to epithelial disease where the mechanics of fluid redistribution could be altered when the epithelium has a mass effect from thickened epithelium of premalignancy, papilloma, or early glottic cancer.

This model emphasizes the importance of the fluid component of the lamina propria in injury prevention and implies that a dehydrated vocal fold could have a reduced capacity to withstand these forces of collision. Consequently, dehydrated vocal fold tissue could have a higher risk of lesions than hydrated vocal fold tissue. Several other studies by Hanson *et al.*^{45,46} have explored aspects of dehydration in the lamina propria, including parameters of dehydration and the rehydration abilities of the tissue. They found that half of the ten samples dehydrated to 30% were able to recover their original volume, while only one of the samples dehydrated to 70% fully recovered its original volume. This finding implies that when the lamina propria is dehydrated to a large extent, it may undergo changes that affect its ability to fully rehydrate. It has been proposed that improper or excessive voice use may lead to dehydration of the lamina propria. However, dehydration in the physiological setting is to a much lesser extent than the 30% dehydration condition utilized in the Hanson experiment, and an *in vivo* larynx likely has a much greater rehydration ability because of its circulatory and lymphatic systems. Therefore, it has been proposed that a period of vocal rest may allow for fluid redistribution within the lamina propria, thus allowing for tissue rehydration and decreasing the likelihood of further vocal fold injury. The notion of voice rest is essential for professional

voice users such as teachers and performers. There are currently no Occupational Safety and Health Administration (OSHA) guidelines related to voice rest for teachers despite the frequency of professionally related dysphonia. Dysphonia in this population and others leads to lost work time and increased cost for any educational system. Furthermore, although poorly studied to date, it is well known that professional voice users, particularly in musical theater, are prone to benign lesions of the vocal fold, inhibiting their professional longevity and success. Thus, this hypothesis has important clinical applications and is worth examining in further studies.

IV. CONCLUSION

In this study, we have developed a self-vibrating vocal folds model that accounts for contact and possesses a biphasic material formulation. This model allows us to study the spatiotemporal characteristics of fluid dynamics in a vibrating vocal folds model. Summarizing the above reported results, the following phenomena and liquid dynamics have been observed in our study:

- (1) Fluid movement lags behind the movement of the solid frame in the time domain, likely due to inertial effects.
- (2) Collision between the left and right vocal folds causes an abrupt change in the fluid distribution around the collision region. Moreover, the duration of collision is so short that the velocity and acceleration of the fluid movement are high.
- (3) In the lateral direction, before vocal fold collision, vibration makes the interstitial fluid content near the medial surface decrease relative to the static condition. During collision, the fluid content is redistributed to the medial surface from the deep tissue.
- (4) In the inferior-superior direction, the fluid in the vocal cover is squeezed from the inferior lip to the superior lip. The fluid is observed to move in the same direction as the mucosal wave propagation.
- (5) In the AP direction, fluid is accumulated at the AP midpoint due to the vibration of the vocal folds, whereas vocal fold collision causes the fluid in the collision zone to leave the region quickly.

Additionally, the current work still has some limitations. The poroelastic parameters, e.g., permeability β , still lack experimental measurements. We have chosen their values according to some anatomical characteristics of vocal fold tissue, for example, we let $\beta_y \ll \beta_{x,z}$ since the permeability of tissue is expected to be significantly higher in the longitudinal direction than in the other directions. The value of these poroelastic parameters could influence the flow property of fluid. For a finite α and β , fluid movement is allowed. As α and β approach infinity, the poroelastic model downgrades into a classic elastic model. Smaller permeability values might imply a fast flux, according to Darcy's law. The major driving force of the liquid movement comes from the tissue deformation during the vocal fold vibration. The tissue deformation squeezes the liquid and causes its

movement. Based on the accuracy of the kinematics of the vocal folds, which have been verified according to the observed surface dynamics, we can expect that the values of the permeability could only affect the magnitude of liquid movement, but did not change the qualitative tendencies of flux in the vibrating vocal folds. Finally, it is notable that the current model is validated based on external vocal fold deformation. It is still lacking true measures of poroelastic coefficients and direct observation of fluid dynamics in the vibrating vocal fold. In further studies, the direct measurements of the liquid dynamics and poroelastic coefficients may make the predicted results more reliable. Also, the quantitative influences of the poroelastic coefficients are worth being investigated by a parameter sweep of these coefficients.

In summary, the poroelastic theory can provide rich spatiotemporal information about interstitial fluid dynamics in the vibrating vocal folds, which cannot be predicted by the often-used elastic solid theory. Valuable fluid dynamics have been observed in this study. The information about fluid motion during vocal fold vibration could be helpful in exploring etiology of some laryngeal pathologies, optimizing disease treatment (e.g., drug delivery in the vibrating tissue), and understanding hemodynamics in the vocal folds.

ACKNOWLEDGMENT

This work was supported by NIH Grant No. 5-R01DC015689-02 from the National Institute of Deafness and other Communication Disorders; the National Natural Science Foundation of China (NSFC) (11874217); and the Fundamental Research Funds for the Central Universities.

- ¹I. R. Titze, "On the mechanics of vocal-fold vibration," *J. Acoust. Soc. Am.* **60**, 1366–1380 (1976).
- ²J. J. Jiang, C. E. Diaz, and D. G. Hanson, "Finite element modeling of vocal fold vibration in normal phonation and hyper functional dysphonia: Implications for the pathogenesis of vocal nodules," *Ann. Otol. Rhinol. Laryngol. Suppl.* **107**, 603–610 (1998).
- ³F. Alipour, D. A. Berry, and I. R. Titze, "A finite-element model of vocal-fold vibration," *J. Acoust. Soc. Am.* **108**, 3003–3012 (2000).
- ⁴E. J. Hunter, I. R. Titze, and F. Alipour, "A three-dimensional model of vocal fold abduction/adduction," *J. Acoust. Soc. Am.* **115**, 1747–1759 (2004).
- ⁵H. E. Gunter, "A mechanical model of vocal-fold collision with high spatial and temporal resolution," *J. Acoust. Soc. Am.* **113**, 994–1000 (2003).
- ⁶C. Tao and J. J. Jiang, "Anterior-posterior biphonation in a finite element model of vocal fold vibration," *J. Acoust. Soc. Am.* **120**, 1570–1577 (2006).
- ⁷D. A. Berry and I. R. Titze, "Normal modes in a continuum model of vocal fold tissue," *J. Acoust. Soc. Am.* **100**, 3345–3354 (1996).
- ⁸S. L. Thomson, L. Mongeau, and S. H. Frankel, "Aerodynamic transfer of energy to the vocal folds," *J. Acoust. Soc. Am.* **118**, 1689–1700 (2005).
- ⁹D. A. Berry, H. Herzel, I. R. Titze, and K. Krischer, "Interpretation of biomechanical simulations of normal and chaotic vocal fold oscillations with empirical eigenfunctions," *J. Acoust. Soc. Am.* **95**, 3595–3604 (1994).
- ¹⁰D. D. Cook, E. Nauman, and L. Mongeau, "Ranking vocal fold model parameters by their influence on modal frequencies," *J. Acoust. Soc. Am.* **126**, 2002–2010 (2009).
- ¹¹B. Schmidt, M. Stingl, G. Leugering, D. A. Berry, and M. Döllinger, "Material parameter computation for multi-layered vocal fold models," *J. Acoust. Soc. Am.* **129**, 2168–2180 (2011).
- ¹²J. P. Noordzij and R. H. Ossoff, "Anatomy and physiology of the larynx," *Otolaryngol. Clin. N. Am.* **39**, 1–10 (2006).
- ¹³M. A. Biot, "Theory of elasticity and consolidation for a porous anisotropic solid," *J. Appl. Phys.* **26**, 182–185 (1955).
- ¹⁴M. A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range," *J. Acoust. Soc. Am.* **28**, 168–178 (1956).
- ¹⁵V. C. Mow, G. A. Ateshian, and R. L. Spilker, "Biomechanics of diarthrodial joints: A review of twenty years of progress," *J. Biomech. Eng.* **115**, 460–467 (1993).
- ¹⁶Y. Zhang, L. Czerwonka, C. Tao, and J. J. Jiang, "A biphasic theory for the viscoelastic behaviors of vocal fold lamina propria in stress relaxation," *J. Acoust. Soc. Am.* **123**, 1627–1636 (2008).
- ¹⁷C. Tao, J. J. Jiang, and Y. Zhang, "A fluid-saturated poroelastic model of the vocal folds with hydrated tissue," *J. Biomech.* **42**, 774–780 (2009).
- ¹⁸C. Tao, J. J. Jiang, and L. Czerwonka, "Liquid accumulation in vibrating vocal fold tissue: A simplified model based on a fluid-saturated porous solid theory," *J. Voice* **24**, 260–269 (2010).
- ¹⁹C. Tao and X. Liu, "Effects of poroelastic coefficients on normal vibration modes in vocal-fold tissues," *J. Acoust. Soc. Am.* **129**, 934–943 (2011).
- ²⁰P. Bhattacharya and T. Siegmund, "A computational study of systemic hydration in vocal fold collision," *Comput. Methods Biomech. Biomed. Eng.* **17**(16), 1835–1852 (2014).
- ²¹P. Bhattacharya and T. Siegmund, "Computational modeling of vibration-induced systemic hydration of vocal folds over a range of phonation conditions," *Int. J. Numer. Methods Biomed. Eng.* **30**, 1019–1043 (2014).
- ²²B. D. Erath, M. Zanartu, and S. D. Peterson, "Modeling viscous dissipation during vocal fold contact: The influence of tissue viscosity and thickness with implications for hydration," *Biomech. Model Mechanobiol.* **16**, 947–960 (2017).
- ²³L. Wu and Z. Zhang, "A computational study of vocal fold dehydration during phonation," *IEEE Trans. Biomed. Eng.* **64**(12), 2938–2948 (2017).
- ²⁴J. J. Jiang and I. R. Titze, "Measurement of vocal fold intraglottal pressure and impact stress," *J. Voice* **8**, 132–144 (1994).
- ²⁵M. M. Hess, K. Verdolini, W. Bierhals, U. Mansmann, and M. Gross, "Endolaryngeal contact pressure," *J. Voice* **12**, 50–67 (1998).
- ²⁶M. Spencer, T. Siegmund, and L. Mongeau, "Determination of superior surface strains and stresses, and vocal fold contact pressure in a synthetic larynx model using digital image correlation," *J. Acoust. Soc. Am.* **123**, 1089–1103 (2008).
- ²⁷L.-J. Chen and L. Mongeau, "Verification of two-minimally invasive methods for the estimation of the contact pressure in human vocal folds during phonation," *J. Acoust. Soc. Am.* **130**, 1618–1627 (2011).
- ²⁸C. Tao, J. J. Jiang, and Y. Zhang, "Simulation of vocal fold impact pressures with a self-oscillating finite-element model," *J. Acoust. Soc. Am.* **119**, 3987–3994 (2006).
- ²⁹I. R. Titze and W. J. Strong, "Normal modes in vocal cord tissues," *J. Acoust. Soc. Am.* **57**(3), 736–744 (1975).
- ³⁰D. D. Cook and L. Mongeau, "Sensitivity of a continuum vocal fold model to geometric parameters, constraints, and boundary conditions," *J. Acoust. Soc. Am.* **121**(4), 2247–2253 (2007).
- ³¹M. Hirano, Y. Kakita, K. Ohmaru, and S. Kurita, "Structure and mechanical properties of the vocal fold," *Speech Lang.* **7**, 271–297 (1982).
- ³²T. Baer, "Investigation of the phonatory mechanism," Status Report on Speech Research SR-66, Haskins Laboratories, New Haven, 35–54 (1981).
- ³³S. Saito, H. Fukuda, S. Kitahara, Y. Isogai, T. Tsuzuki, H. Muta, E. Takayama, T. Fujioka, N. Kokawa, and K. Makino, *Vocal Fold Physiology: Biomechanics, Acoustics, and Phonatory Control*, edited by I. R. Titze and R. C. Scherer (Denver Center for the Performing Arts, Denver, CO, 1985).
- ³⁴M. Döllinger, D. A. Berry, and G. S. Berke, "Medial surface dynamics of an in vivo canine vocal fold during phonation," *J. Acoust. Soc. Am.* **117**, 3174–3183 (2005).
- ³⁵S. D. Gray, M. Hirano, and K. Sato, "Molecular and cellular structure of vocal fold tissue," in *Vocal Fold Physiology: Frontiers of Basic Science*, edited by I. R. Titze (Singular, San Diego, CA, 1993), pp. 1–34.
- ³⁶F. Alipour and I. R. Titze, "Elastic models of vocal fold tissues," *J. Acoust. Soc. Am.* **90**(3), 1326–1331 (1991).
- ³⁷R. W. Chan and I. R. Titze, "Viscoelastic shear properties of human vocal fold mucosa: Measurement methodology and empirical results," *J. Acoust. Soc. Am.* **106**, 2008–2021 (1999).
- ³⁸C. Tao, Y. Zhang, and J. J. Jiang, "Extracting physiologically relevant parameters of vocal folds from high-speed video image series," *IEEE Trans. Biomed. Eng.* **54**, 794–801 (2007).

- ³⁹I. R. Titze, "Parameterization of the glottal area, glottal flow, and vocal fold contact area," *J. Acoust. Soc. Am.* **75**, 570–580 (1984).
- ⁴⁰D. G. Hanson, J. J. Jiang, M. D'Agostino, and G. Herzon, "Clinical measurement of mucosal wave velocity using simultaneous photoglottography and laryngostroboscopy," *Ann. Otol. Rhinol. Laryngol.* **104**, 340–349 (1995).
- ⁴¹J. J. Jiang, C.-I. B. Chang, J. R. Raviv, S. Gupta, F. M. Banzali, and D. G. Hanson, "Quantitative study of mucosal wave via videokymography in canine larynges," *Laryngoscope* **110**, 1567–1573 (2000).
- ⁴²Y. W. Shau, C. L. Wang, F. J. Hsieh, and T. Y. Hsiao, "Noninvasive assessment of vocal fold mucosal wave velocity using color Doppler imaging," *Ultrasound Med. Biol.* **27**, 1451–1460 (2001).
- ⁴³L. Czerwonka, J. J. Jiang, and C. Tao, "Vocal nodules and edema may be due to vibration-induced rises in capillary pressure," *Laryngoscope* **118**, 748–752 (2008).
- ⁴⁴H. S. Bonilha, A. Aikman, K. Hines, and D. D. Deliyski, "Vocal fold mucus aggregation in vocally normal speakers," *Logoped. Phoniatr. Vocol.* **33**(3), 136–142 (2008).
- ⁴⁵K. P. Hanson, Y. Zhang, and J. J. Jiang, "Ex vivo canine vocal fold lamina propria rehydration after varying dehydration levels," *J. Voice* **25**, 657–662 (2011).
- ⁴⁶K. P. Hanson, Y. Zhang, and J. J. Jiang, "Parameters quantifying dehydration in canine vocal fold lamina propria," *Laryngoscope* **120**, 1363–1369 (2010).