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3aMU5. Influence of epithelium and fiber locations on glottal closure and sound production at soft-phonation conditions

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Previous studies showed that isotropic vocal fold models often vibrated with incomplete glottal closure at onset despite the vocal folds were in contact at rest. This contrasts with human phonation in which complete glottal closure is observed even during soft phonation with minimal or low laryngeal muscle contraction. Based on previous experimental studies, we hypothesize that this difference in glottal closure patterns is due to the relatively large stiffness in the anterior-posterior direction or the presence of the epithelium layer. These hypotheses were tested in self-oscillating physical vocal-fold models, with anisotropic stiffness conditions simulated by fibers loosely imbedded at different locations in otherwise isotropic vocal folds. The results showed that, compared to isotropic one-layer models, the presence of a stiff epithelium layer led to complete glottal closure along the anterior-posterior direction, increased maximum glottal opening, strong excitation of high-order harmonics in the resulting voice spectra and reduced noise production. Similar improvement in glottal closure and high-order harmonics excitation was observed with fibers in the cover layer, but to a less degree. Presence of fibers in the body-layer led to reduced maximum glottal opening but did not yield noticeable improvement in glottal closure and harmonic excitation. [Work supported by NIH.]

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INTRODUCTION

An important feature of normal voice production is the complete glottal closure during part of the vocal fold oscillation cycle. The abrupt decrease in the flow rate due to complete glottal closure allows humans to produce voice with harmonic contents at frequencies well above the oscillation frequency of the vocal folds. Complete glottal closure also disrupts the development and persistence of a turbulent jet flow and thus reduces noise production and the overall breathiness of the produced voice. In humans, complete glottal closure is observed in voice production at different levels of pitch and loudness.

However, recent experiments using self-oscillating physical models (Thomson et al., 2005; Zhang et al., 2006a,b; Zhang, 2011) showed that isotropic physical models had the tendency to be deformed vertically (flow direction) and laterally so that the glottis was blown open at onset despite that the two vocal fold models were brought into contact at rest, resulting in incomplete glottal closure and production of sound of a high breathy quality. For these isotropic models, although the vocal fold model was able to come back to glottal midline during closing, the contact between the two vocal folds was brief and often occurred at the middle along the anterior-posterior direction. This contrasts with human vocal folds which are able to vibrate with the glottis closed for a considerably long portion of the oscillating cycle, even at soft phonation conditions when the vocal folds are at a relaxed state.

Human vocal folds are of course not isotropic in either the body or the cover layer. The vocal folds consist of an inner muscular layer, several lamina propria layers, and an outmost epithelium layer. Early studies by Hirano and Kakita (1985) showed that both the muscular layer and the lamina propria are at least transversely-isotropic (due to the presence of muscle fibers and collagen), with the Young's modulus in the anterior-posterior (AP) direction at least 5-8 times larger than the transverse Young's modulus. Zhang (2011) showed that vocal folds with a higher stiffness in the AP direction would significant reduce the vertical deformation as observed in the isotropic models. The epithelium is a very thin layer with an estimated Young's modulus of 100 kPa. Hirano and Kakita (1985) argued that the epithelium can be treated as isotropic due to its extremely small thickness (about 0.05-0.08 mm). Due to its large stiffness relative to other layers, the epithelium may further reduce the vertical deformation of the vocal folds (Gunter, 2003) and thus allow the vocal folds to better maintain their adductory position, at least at soft phonation conditions.

Physical models with features approximating the epithelium layer and fibers have been used in previous studies. For example, Titze *et al.* (1995) attached a silicone epithelium membrane onto a stainless steel flat surface and filled the air gap with fluids of varying viscosities between them to study the phonation onset pressure and glottal width. Ruty et al. (2007) used an vocal fold model based on water-filled latex tubes with controllable water pressure. Although not explicitly designed to simulate the epithelium layer, the latex membrane functioned equivalently as an epithelium layer. Recently, the effects of an epithelium layer on vocal fold vibration were investigated in a layered silicone vocal fold model (Murray and Thomson, 2012). Acrylic and polyester fibers were also added in this silicone physical model (Shaw et al., 2012) in order to simulate the nonlinear material property in the vocal fold cover. As these previous studies generally focused on other aspects of phonation, the possible effects of the presence of an epithelium layer and embedded fibers on the glottal closure pattern and sound production have thus not been investigated.

The goal of this study was to investigate the possible roles of the epithelium and embedded fibers in the glottal closure pattern and sound production, using physical vocal fold models of different structural properties. We will show that adding a thin stiff outer layer to an otherwise isotropic model produced complete glottal closure, which led to more excitation of high-order harmonics. Similar improvement in the glottal closure pattern was also achieved with fibers embedded in the cover layer. Embedding fibers in the body layer however did not produce noticeable improvement.

METHODS

The details of the experimental setup were described in previous studies (Zhang *et al.*, 2006a,b; Zhang, 2011). The setup consisted of an expansion chamber (with a rectangular cross-section of the dimension 23.5×25.4 cm and 50.8-cm long) simulating the lungs, an 11-cm-long straight circular PVC tube (inner diameter of 2.54 cm) simulating the tracheal tube, and a self-oscillating vocal fold model. The expansion chamber was connected upstream to a pressurized airflow supply through a 15.2-m-long rubber hose. No vocal tract was used in this study to avoid possible source-tract interaction.

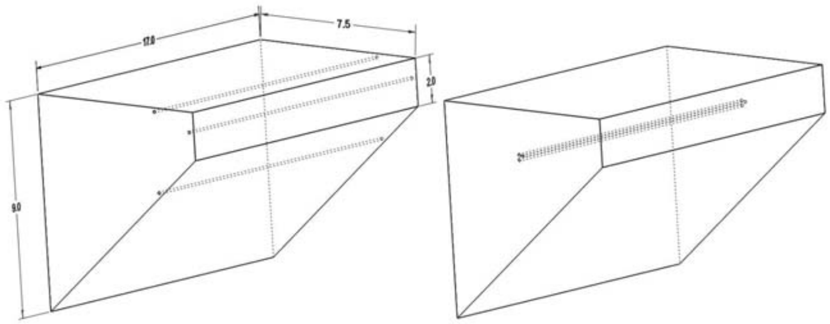

FIGURE 1. Geometry of the Vocal folds physical model and embedded fiber position in cover (a) and body (b). Dimensions are in mm.

Six vocal fold models of identical geometry but different structure composition were fabricated and used in this study. All vocal folds had a medial surface thickness of 2 mm along the inferior-superior direction and a depth of 7.5 mm along the medial-lateral direction. A one-layer isotropic model as used in previous studies (Zhang *et al.*, 2006b; Zhang, 2010) was used as the baseline model (M1), whereas other models included a stiff thin epithelium layer, or embedded fiber bundles, or both features (Table 1). The baseline model was fabricated by mixing a two-component silicone compound solution (Ecoflex 0030, Smooth-on, Easton, PA) with a silicone thinner (Smooth-on, Easton, PA) at a 1:1:5 weight ratio, which yielded a Young's modulus about 2.5 kPa. The epithelium layer was added by spreading a silicone mixture solution (Ecoflex 0030, weight ratio of 1:1, with a Young's modulus of 60 kPa) over all surfaces of the baseline model. For models with embedded fibers, the silicone compound solution was first poured to fill the bottom half of the models and short polyethylene fiber threads (aligned along the anterior-posterior direction) were added to the top of the vocal fold before the compound solution was fully cured. Additional silicone compound solution was then added to fill top half of the model. No pretension was applied to the fiber threads. Two fiber embedding patterns within the vocal fold were investigated, with fibers located approximately in the body layer (M2 and M5) or the cover layer (models M3 and M6), as shown in Fig. 1. In order to enhance the bonding between the silicone rubber and the fiber bundles, the fiber threads were soaked in the silicone primers (Dow Corning, Midland, MI) and dried for half an hour before aligned to the predefined positions. The mixture were cured for 1 hour at 75 °C and then two days in room temperature. The lateral, anterior and posterior surfaces of the physical vocal fold were glued to a rectangular groove on an acrylic plate.

TABLE 1. Structural composition of the six vocal fold models used in this study.

Model	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
Epithelium	No	No	No	Yes	Yes	Yes
Fiber location	No fibers	Body	Cover	No fibers	Body	Cover

For each vocal fold model, the subglottal pressure was gradually increased in discrete increments from zero to 20% above the phonation threshold pressure. At each step, after a delay of about 1–2 s after the flow rate change, the mean subglottal pressure (measured at 2 cm from the entrance of the glottis), mean flow rate, acoustic pressure inside the tracheal tube (2 cm from the entrance of the glottis), and outside acoustic pressure (about 20 cm downstream and about 30° off axis) were measured for a 1-s period. These data were recorded at a sampling rate of 50 kHz. High speed cameras were used to image vocal fold vibration from a superior view at 2000 fps, from which the glottal area waveform was extracted using a Matlab-based program.

RESULTS

Figure 2 shows the phonation threshold pressure, onset frequency, threshold flow rate, and outside acoustic pressure at onset for all six models. Generally the presence of a stiff epithelium layer had a much larger effect than the embedded fibers. This is expected because the epithelium layer covered the entire vocal fold surface whereas the embedded fibers only occupied a much smaller volume fraction of the vocal fold model.

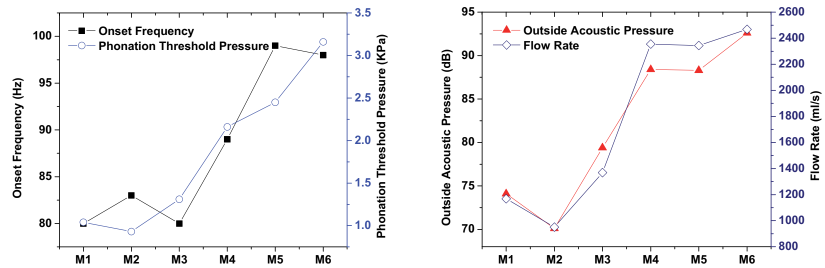

FIGURE 2. a) Phonation threshold pressure and onset frequency and b) phonation threshold flow rate and outside acoustic pressure for the six vocal fold models.

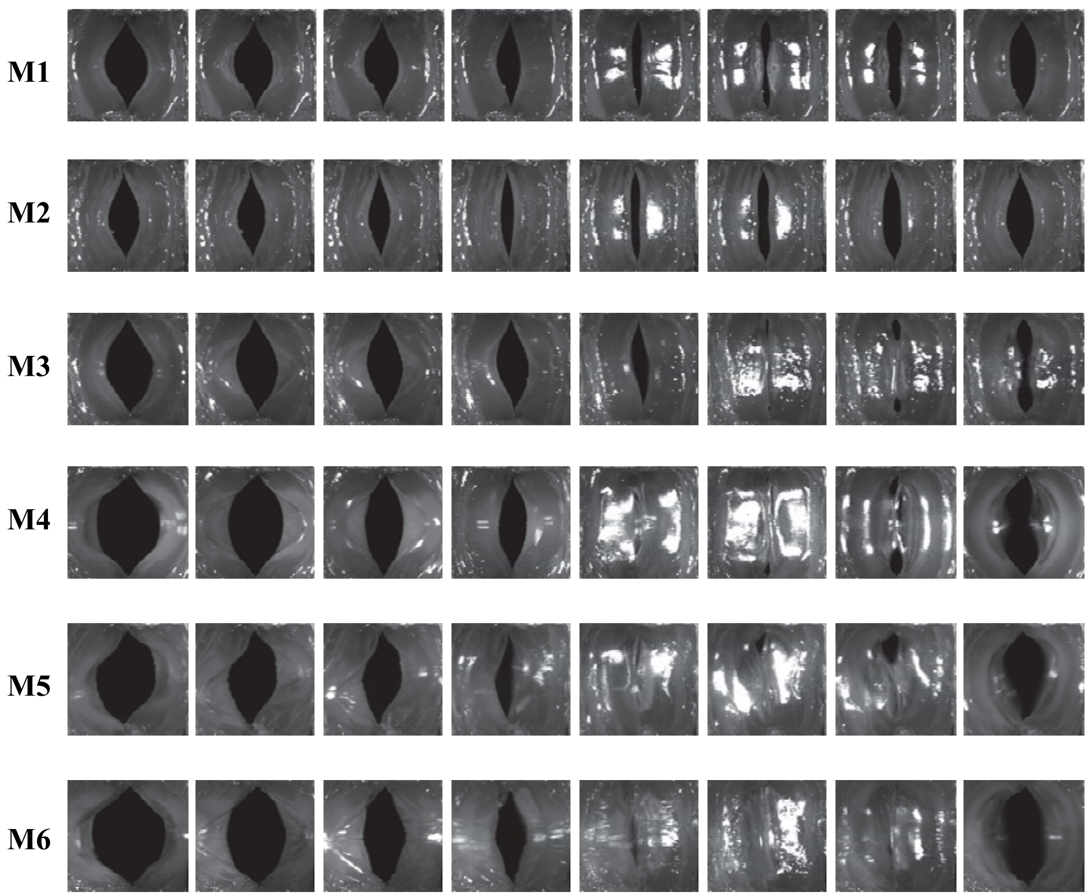

FIGURE 3. Superior view of M1-S to M6-S models in one cycle with equal intervals.

Figure 3 shows superior-view images of the vocal folds at onset during one oscillating cycle, and the extracted glottal area waveforms for all six models are shown in Fig. 4a. The baseline model, M1, did not produce complete glottal closure, with a minimum glottal area of about 10 mm^2. Compared to the baseline model, embedding fibers in the body layer did not reduce the minimum glottal area but significantly reduced the maximum glottal opening area. Embedding fibers in the cover layer however, allowed the glottis to be completely closure(as indicated by zero minimum glottal area), although only briefly, and also led to an increased maximum glottal opening area. The most significant improvement in the glottal closure pattern was achieved with the presence of a stiff epithelium layer. Complete glottal closure was achieved in all three models with an epithelium layer (M4, M5, and M6), with or without fibers. The longest closure time was achieved in model M6 with both the epithelium layer and fibers in the cover layer, with a closed quotient of 0.29, and decreased to 0.14 and 0.13 for M5 and M4, respectively.

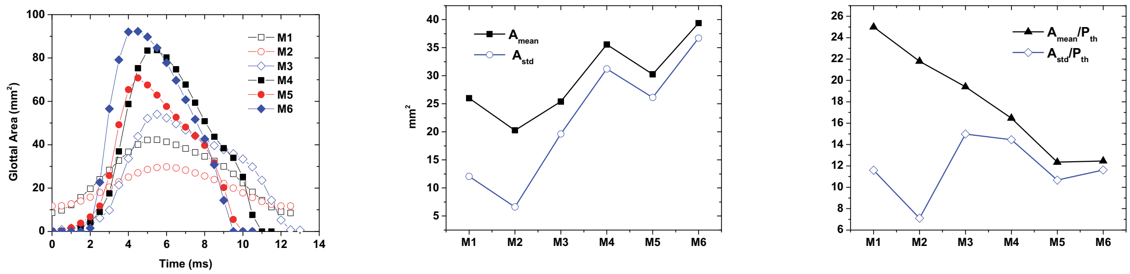

FIGURE 4. a) glottal area waveform for one cycle for the six vocal fold models; b) the mean glottal opening area (A_{mean}) and glottal vibration amplitude (A_{std}); and c) the mean glottal opening area and glottal vibration amplitude normalized by phonation threshold pressure.

Fig. 4b shows the mean glottal area and the glottal vibration amplitude (estimated as the standard deviation of the glottal area waveform) for all six models. Both the mean glottal opening and the vibration amplitude increased from M1 to M6, except for M2. Because this increase in vibration amplitude was also accompanied by an increase in phonation threshold pressure, one may assume that the increasing subglottal pressure may increase the vibration amplitude and thus improve the glottal closure pattern. However, in our experiments, increasing the subglottal pressure further beyond onset in the baseline model M1 led to increased vibration amplitude but did not lead to complete glottal closure. Thus, increasing pressure or increasing vibration amplitude alone was not enough to cause complete glottal closure.

Fig. 4c shows the mean glottal opening area and the glottal vibration amplitude normalized by phonation threshold pressure. The normalized glottal vibration amplitude stayed relative constant across all models except for M2. In contrast, the normalized mean glottal opening decreased monotonically from M1 to M6. Thus, for models without an epithelium layer, the glottal vibration amplitude was much smaller than the mean glottal opening (thus incomplete glottal closure), whereas the glottal vibration amplitude was comparable to the mean glottal openings for models with epithelium (thus complete glottal closure). This indicates that the improvement in the glottal closure pattern may be due to the reduction in the ratio between the mean glottal opening and the glottal vibration amplitude. Both the presence of the epithelium layer and fibers in the cover layer were able to, for a given subglottal pressure, reduce the mean vocal fold deformation but maintain the same vibration amplitude, thus allowing the glottis to be complete closed. In contrast, presence of fibers in the body layer reduced both the mean vocal fold deformation and the glottal vibration amplitude, thus did not produce noticeable improvement on the glottal closure pattern.

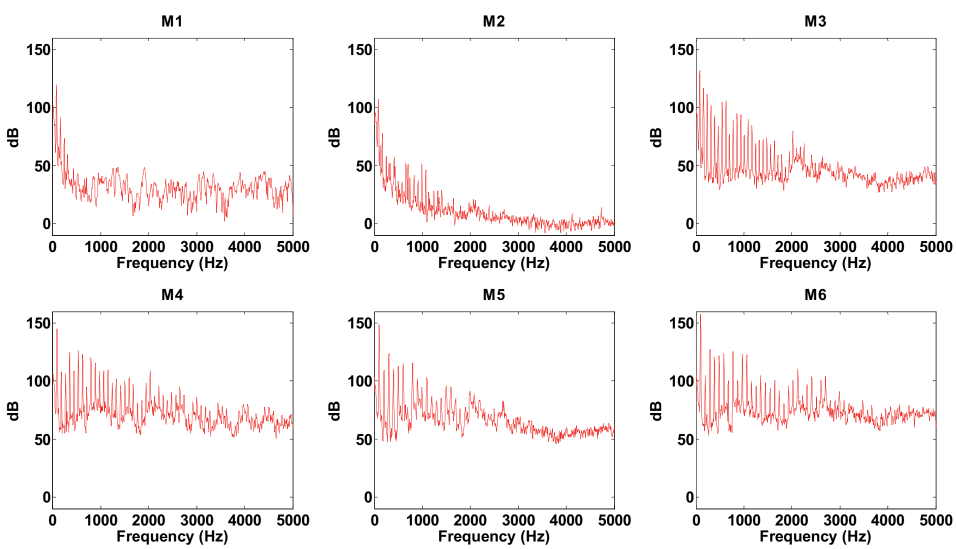

FIGURE 5. Spectra of the outside sound produced by the six vocal fold models at onset.

Figure 5 shows the spectra of the outside sound pressure at onset for all six models. In general, improvement in the glottal closure pattern led to more excitation of high-order harmonics in the outside sound spectra, comparing M3-M6 to M1 and M2, which produced a more brighter sound quality in models M4-M6. The sound pressure level was also much higher in models with complete glottal closure than models without. On the other hand, models with large vibration amplitude also led to more noise production at higher frequencies, presumably due to the large flow rate.

DISCUSSION

Although one-layer isotropic models often led to incomplete glottal closure, this study showed that adding a stiff outer layer or embedding fibers aligned along the AP direction in the cover layer were able to produce complete glottal closure. Our results further showed that such improvement in the glottal closure pattern was because both features (the presence of an epithelium layer or fibers in the cover layers) were able to reduce the static vocal fold deformation (or the mean glottal opening) without simultaneously reducing the glottal vibration amplitude, as shown in Fig. 4c. This is in contrast to embedding fibers in the body layer as in model M2 or stiffening the body-layer as in Zhang (2011), which simultaneously reduced the mean glottal opening and the vibration amplitude.

Our numerical analysis showed that, for a given subglottal pressure, the vocal fold static deformation along the medial-lateral direction was significantly reduced with the addition of a stiff outer layer or fibers in the cover layer. However, it is unclear why such reduction was not observed for the dynamic vibration amplitude. On the other hand, the presence of a stiff outer layer or fibers in the cover layer may have changed the structural dynamics and the interaction with the glottal flow. In particular, it was observed that, for models with complete glottal closure, the vocal fold medial surface generally vibrated in a more in-phase pattern along the AP direction, i.e., the entire vocal fold edge along the AP direction moved toward and away from the glottal midline together. In contrast, for models with incomplete glottal closure, the vocal fold edge exhibited an out-of-phase medial-lateral motion along the AP direction. Specifically, the middle portion of the vocal fold surface moved out-of-phase with the anterior and posterior edges so that when the middle part moved towards the glottal midline the AP edges were already moving away from the glottal midline, thus preventing complete glottal closure. Eigenmode analysis using finite-element models showed that both the second and third eigenmodes of the one-layer isotropic model (M1) exhibited strong AP out-of-phase motion. This AP out-of-phase motion was either suppressed or significantly weakened in the first few lower-order eigenmodes in models with a stiff outer layer or embedded stiff fibers along the AP direction in the cover layer. Because generally only the first few vocal fold eigenmodes are excited during phonation (Zhang et al., 2007; Zhang, 2010), this would lead to a more in-phase vocal fold motion along the AP direction, thus facilitating complete glottal closure, as shown in this study. This will be further investigated in future studies.

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