Abstract: Synthetic models are used to study vocal fold flow-induced vibration. Advantages include reproducibility and vibration frequencies typical of human phonation. Limitations of recent models include lack of a mucosal wave, excessive inferior-superior motion, and limited convergent-divergent motion. To overcome these limitations, a synthetic vocal fold model was developed that included separate epithelial and lamina propria layers. A corresponding finite element model was developed. High-speed imaging was used to quantify synthetic model motion, including videokymography and determination of three-dimensional marker trajectories. Both models exhibited similar characteristics in terms of vibration frequency (around 115 Hz) and maximum glottal width (just under 2 mm). The synthetic model onset pressure was 0.4 kPa, which is significantly lower than many previous synthetic models. These values are consistent with human phonation. Importantly, in both models mucosal wave-like motion was evident and alternating convergent-divergent intraglottal profiles were seen. These advantages will be useful in future experiments and simulations by providing models that exhibit more life-like response and motion. The two models are described, data are presented, significance of the models is discussed, and suggestions for future work are provided.

Keywords: Vocal fold models, artificial models, finite element models

I. INTRODUCTION

Computational and experimental models are used to study vocal fold flow-induced vibration. Many recent models are based on some variation of the multi-layer structure presented by Hirano [1]. Computational models include high-fidelity Navier-Stokes flow solvers coupled with solid models that include cover, ligament, and body layers [2,3]. Synthetic models include epithelium-lamina propria configurations [4] and two-layer body-cover silicone models [5]. The recent two-layer synthetic models are useful because of their reproducibility, low cost, and ease of parameterization. They have a length scale similar to that of the human vocal folds, have layers with differing stiffness, and vibrate at frequencies typical of human phonation.

Most recent synthetic models are currently limited by three features: unnaturally large inferior-superior displacement, lack of a clear mucosal wave, and higher-than-desired onset pressure (usually 1 to 2 kPa, compared with 0.2 to 0.4 kPa for human phonation). These limitations have been attributed in part to the models’ cover layers being stiffer than the human cover. The Young’s modulus of elasticity values of the model covers have been around 2 to 3 kPa. By contrast, cover shear modulus values around 0.25 kPa (corresponding to Young’s modulus values around 0.75 kPa) at 100 Hz have been measured [6].

To overcome these limitations, a synthetic vocal fold model was developed that includes a cover layer that, as is the case with the human vocal folds, included two distinct layers: a thin epithelial layer and an underlying flexible layer that represented the superficial lamina propria. This synthetic model and a corresponding finite element model are described below. Data are presented which demonstrate significant improvements in terms of model motion and onset pressure.

II. METHODS

A. Synthetic Model

The synthetic model geometry is shown in Fig. 1. Silicone interior layers were fabricated according to the multi-layer rapid prototyping, molding, and casting procedures described in [5,7]. The epithelial layer was created by pouring a silicone mixture over the assembled interior layers. The epithelial layer thickness was estimated to be approximately 0.1 mm. Layer Young’s moduli were controlled by varying the pre-cured silicone mixture content; values for the different layers were approximately 11.8 kPa (body), 1.6 kPa (ligament), 0.2 kPa (superficial lamina propria), and 49.8 kPa (epithelium). Tension was applied to a fiber thread that ran anteriorly-posteriorly within the ligament layer to reduce inferior-superior motion. High-speed video imaging (Photron SA3, 3000 frames per second) was used to capture model motion.
B. Finite Element Model

The finite element model consisted of two-dimensional, fully-coupled fluid and solid domains, as shown in Fig. 2. The solid model incorporated the same geometry as the synthetic model, but with a 50 \( \mu \)m-thick epithelium. The material properties were also the same, with the exception that the superficial lamina propria layer material property was based on a nonlinear stress-strain curve. This curve was governed by the equation

\[ \sigma(\varepsilon) = 11.2(e^{0.5\varepsilon} - 1), \]

where \( \sigma \) is stress (Pa) and \( \varepsilon \) is strain. This yielded a tangent modulus of 200 Pa at \( \varepsilon = 0.05 \) and 972 Pa at \( \varepsilon = 0.2 \). The finite element model did not include a fiber.

The fluid model used an incompressible, viscous, 2D, unsteady Navier-Stokes solver with a constant 600 Pa inlet pressure. The solid domain allowed for large strain and large deformation and included Rayleigh damping \((\alpha = 101.67, \beta = 0.0001073)\) for energy dissipation.

Solution was accomplished using the commercial code ADINA. A time step size of \( 10^{-4} \) and a second-order composite time marching scheme were used. For computational efficiency, medial-lateral symmetry was assumed. The fluid domain consisted of 7340/7641 1st-order elements/nodes and the solid domain consisted of 2359/2582 1st-order elements/nodes (see Fig. 3). A solution for 1500 time steps required approximately 3.2 hours on a single 2.53 GHz Intel P9500 processor.

III. RESULTS

The synthetic model had an onset pressure of 400 Pa. At a pressure 20% above onset pressure (480 Pa), the vibration frequency was 114.5 Hz and the maximum glottal width was approximately 1.8 mm. These values compare well with those of human phonation.

Importantly, mucosal wave-like motion was evident and the inferior-superior motion appeared to be lower than with previous two-layer models. To capture this wave-like motion, a hemilarynx configuration and two synchronized high speed cameras (Photron SA3, 3000 frames per second) were used to track the medial surface position in a manner similar to that described in [8]. One sample image is shown in Fig. 4 in which ink dots placed on the model surface are visible. The medial-lateral trajectories (three-dimensional positions) of the dots in the center column were tracked over several oscillation periods, as shown in Fig. 5. A wave-like motion clearly propagated superiorly along the medial surface, and an alternating convergent-divergent medial surface profile was visible. Evidence of this convergent-divergent motion can also be seen in the kymogram shown in Fig. 6 (obtained using a single high-speed camera and a full larynx configuration).
Figure 6. High-speed kymogram of several periods of the synthetic model during flow-induced vibration. The pressure was 0.48 kPa and the frequency was 114.5 Hz.

Figure 7. Finite element model glottal width vs. time. Top: entire simulation. Bottom: Two steady-state periods.

IV. DISCUSSION

The synthetic and computational models exhibited similar characteristics in terms of vibration frequency and amplitude. Some differences in motion were observed; for example, unlike the synthetic model, the numerical model did not experience complete glottal closure during vibration. Differences in motion of the two models were attributed to four factors: differences in material properties (stress vs. strain relationships, Poisson’s ratio, and damping coefficients), three-dimensionality of the synthetic model versus two-dimensionality of the finite element model, difference in thickness of the epithelial layer, and presence of an anterior-posterior fiber in synthetic model.

V. CONCLUSION

Complementary synthetic and finite element models of the vocal folds have been developed and tested. The models were based on the same multi-layer geometry. Each included a cover layer that was comprised of a thin epithelial layer and a very flexible layer that was similar to the superficial lamina propria. Each also included
ligament and body layers, and the synthetic model included a fiber imbedded within the ligament layer.

In both models mucosal wave-like motion was evident. Alternating convergent-divergent intraglottal profiles were also seen. The vibration frequencies and glottal amplitudes were typical of adult human male phonation. Further, the synthetic model had an onset pressure that was much lower than previous models and that is comparable to human phonation. These advantages will be useful in future experiments and simulations by providing models that exhibit more life-like response and motion.

For both models future work includes the use of anisotropic materials. Incorporation of a downstream duct (to simulate the vocal tract) in the synthetic model will also be important. For the finite element model, future work includes performing extensive numerical verification studies (e.g., ensuring that the solutions are independent of grid density and time step size), extending the model to three dimensions, and removing the symmetry condition. The latter will enable the study of asymmetric aerodynamics and vocal fold properties. Potential future work also includes investigation of the influence of epithelial layer thickness and of the material properties of the different layers on model response.

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REFERENCES