A Synthetic, Self-Oscillating Vocal Fold Model Platform for Studying Augmentation Injection

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Summary: Objective. To design and evaluate a platform for studying the mechanical effects of augmentation injections using synthetic, self-oscillating vocal fold models.

Study Design. Basic science.

Methods. Life-sized, synthetic, multilayer, self-oscillating vocal fold models were created that simulated bowing via volumetric reduction of the body layer relative to that of a normal, unbowed model. Material properties of the layers were unchanged. Models with varying degrees of bowing were created and paired with normal models. Following initial acquisition of data (onset pressure, vibration frequency, flow rate, and high-speed image sequences), bowed models were injected with silicone that had material properties similar to those used in augmentation procedures. Three different silicone injection quantities were tested: sufficient to close the glottal gap, insufficient to close the glottal gap, and excess silicone to create convex bowing of the bowed model. The above-mentioned metrics were again taken and compared. Pre- and post-injection high-speed image sequences were acquired using a hemilarynx setup, from which medial surface dynamics were quantified.

Results. The models vibrated with mucosal wave–like motion and at onset pressures and frequencies typical of human phonation. The models successfully exhibited various degrees of bowing which were then mitigated by injecting filler material. The models showed general pre- to post-injection decreases in onset pressure, flow rate, and open quotient and a corresponding increase in vibration frequency.

Conclusion. The model may be useful in further explorations of the mechanical consequences of augmentation injections.

Key Words: Vocal fold medialization–Injection–Bowing–Synthetic vocal fold models–Medial surface dynamics–Direct linear transformation.

INTRODUCTION

Vocal fold bowing can be caused by various pathologies such as scarring,[1] structural changes due to aging (presbylarynx),[2] and thyroarytenoid muscle atrophy caused by complete or partial paralysis.[3] The consequence is that one or both of the vocal folds experience inadequate vocal fold closure (glottal incompetence), generally causing a breathy voice and reduced sound intensity. Because extra effort is required to overcome glottal incompetence, prolonged or loud speech is limited.[4]

Procedures such as medialization laryngoplasty and augmentation injections have yielded success in correcting glottal incompetence. However, obtaining consistent results in terms of correcting the glottal gap and restoring desired vibratory function remains a challenge, and there is much to learn about how these surgical procedures influence vocal fold flow-induced vibration. A method for studying the pre- and post-injection vibratory responses could enable detailed explorations of the physical mechanisms that govern the associated airflow-tissue interactions.

In recent years, synthetic, self-oscillating vocal fold models have been increasingly used to explore the physics of vocal fold vibration.[5] Membranous models approximating the epithelium and superficial layer of the lamina propria have been developed and used to study the effects of epithelium thickness, cover viscosity, and intraglottal angle on vocal fold vibration.[6–8] Molded models have also been developed[9–20] and used to study subglottal flow,[11] flow-structure interactions,[12] supraglottal flow,[13,14] material asymmetries,[15–17] and contact stress.[18] They have also been used to develop and test tools for measuring glottal width and vocal fold length *in vivo*[19] and for estimating vocal fold mechanical properties.[20]

These molded models have typically consisted of either one material layer or two material layers of differing stiffness. They have exhibited similarities with human vocal fold vibration with respect to vibration frequency, glottal width amplitude, and vibratory pressure. Advantages of these models include reproducibility, low cost, and ease of parameterization. Primary disadvantages have included unnaturally large inferior-superior displacement, lack of a clear mucosal wave, in some cases, higher-than-desired onset pressure (usually 1–2 kPa, compared with 0.2–0.4 kPa for human phonation), and a generally divergent profile during vibration.[21,22]

In this research, a multilayer self-oscillating synthetic vocal fold model was used as a test bed for quantifying pre- and post-injection vibratory responses. This model has been shown to overcome some of the above-mentioned disadvantages of one- and two-layer models, notably by operating with an onset pressure comparable with human phonation (around 300–400 Pa) and exhibiting mucosal wave–like motion, reduced inferior-superior motion, and an alternating

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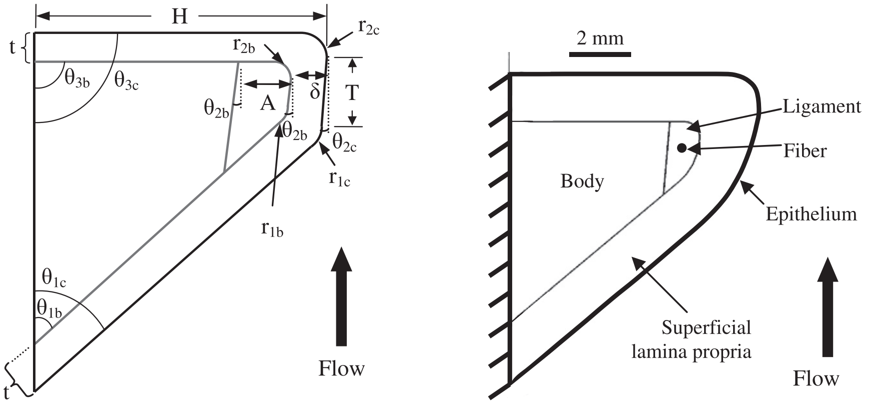

FIGURE 1. Left: parameters defining vocal fold geometry. Right: cross-section of normal model used in this study, from Ref.[22]

convergent-divergent motion during vibration.[22] In this research, bowed synthetic models were created, materials were injected to correct for bowing, and the flow-induced responses of the synthetic models before and after injections were compared. In the following sections, the model fabrication and testing procedures are outlined and results are presented that demonstrate the potential for the test setup to be used to study mechanical effects of augmentation injections.

METHODS

Synthetic model

The previously developed[22] multilayer, synthetic, self-oscillating vocal fold model was used (Figure 1). This model included silicone body, ligament, superficial lamina propria, and epithelium layers, each of different stiffness. The model also included an acrylic fiber in the center of the ligament layer, oriented in the anterior-posterior direction. This fiber was intended to approximate the anisotropy of the ligament in a manner such that inferior-superior motion was reduced; this effect is demonstrated and discussed in Murray and Thomson.[22] (The other layers were isotropic, although the use of anisotropic materials such as those recently described elsewhere[23,24] would be recommended in future studies.) The model geometry was altered to simulate two degrees of bowing (Figure 2). The normal, baseline geometry was defined using the parameters shown in Figure 1 and listed in Table 1. A medial-lateral dimension at the model center was defined as shown in Figure 3. For the bowing cases, this dimension was decreased by either 10% or 20% of its original value by reducing the body layer volume. No change was made to the layer material properties, and the relative geometries followed the changes made to the body such that their relative dimensions (eg, superficial lamina propria thickness) were the same for the bowed and unbowed models.

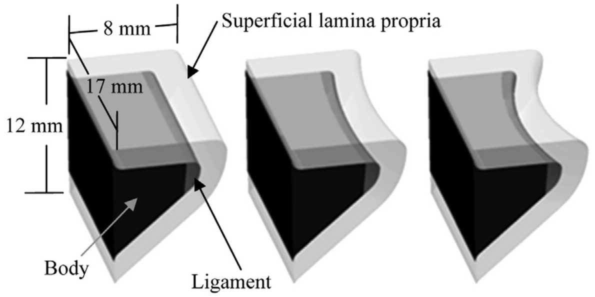

FIGURE 2. Perspective views of normal model (left), 10% (middle), and 20% (right) bowed models. Flow is from bottom to top. Epithelium and fiber not shown.

Model fabrication, complete details of which can be found elsewhere,[22,25] proceeded as follows. Three-dimensional computer models were used to generate rapid prototype models, from which molds for the different layers were created. The models were made by casting the layers using three-part addition-cure silicone. Using different silicone mixing ratios for the different layers allowed for cured layers of different stiffness to be fabricated. The anterior, posterior, and lateral surfaces of the models were adhered to acrylic mounting plates in a manner similar to that which has been previously described.[9] The model mounting plate assemblies were attached to the end of a flow supply tube (described below) for testing.

For each model, a stiff thread, oriented in the anterior-posterior direction, was imbedded in the ligament layer to

TABLE 1.
Geometric Parameters and Description Used to Define Model

Parameter	Value	Description
$\theta_{1b,c}$	50°	Inferior glottal angle
$\theta_{2b,c}$	5°	Intraglottal angle
$\theta_{3b,c}$	90°	Superior glottal angle
r_{1c}	6.0 mm	Cover entrance radius
r_{2c}	0.987 mm	Cover exit radius
r_{1b}	2.0 mm	Ligament entrance radius
r_{2b}	0.513 mm	Ligament exit radius
T	0.1 mm	Vertical glottal thickness
t	1.6 mm	Inferior and superior cover layer thickness
δ	2.0 mm	Maximum medial cover layer thickness
D	8.4 mm	Lateral depth
A	1 mm	Ligament layer thickness