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

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Abstract

Objective—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, multi-layer, 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.

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Keywords

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 vivo¹⁹ 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 to 2 kPa, compared with 0.2 to 0.4 kPa for human phonation), and a generally divergent profile during vibration.^{21,22}

In this research a multi-layer 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 to human phonation (around 300 to 400 Pa) and exhibiting mucosal wave-like motion, reduced inferior-superior motion, and an alternating 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-developed²² multi-layer, synthetic, self-oscillating vocal fold model was used (see 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 (e.g., superficial lamina propria thickness) were the same for the bowed and unbowed models.

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 reduce inferior-superior motion during model vibration. Tension was applied to the thread by suspending weights (31 g each) to the anterior and posterior ends of the thread that extended beyond the model anterior and posterior surfaces. The 31 g weight was selected because it applied tension to the fiber sufficient to reduce the inferior-superior motion while not making the thread completely rigid. The thread and weights were directed such that the thread was only pulled in the anterior-posterior direction.

Material Properties—To quantify material properties, test specimens were made concurrently with fabrication of each layer. Body, ligament, epithelium, and injection material Young's modulus values were determined by testing cylindrical (50 mm long, 8 mm diameter) specimens in an Instron 3342 tensile-testing apparatus. Each specimen was elongated to 40% strain first during a 10 iteration pre-cycling phase at a rate of 1,000 mm/min, followed by one cycle at 10 mm/min. The Young's modulus was determined by fitting a linear curve through the final cycle data at 20% strain. Rheological properties (elastic and viscous shear moduli) of the various silicone layers were determined by testing disks (2 mm thick, 40 mm diameter) in a precision rheometer (TA Instruments AR 2000EX). Each specimen was subject to an oscillatory sweep from 0.1 to 100 Hz and 4% strain.

Tensile test results for the body, ligament, epithelium, and injection materials are listed in Table 2. Since all models were not made simultaneously, multiple material samples were made (one sample for each layer for each model), and the average Young's modulus value for each layer is shown in Table 2, along with the corresponding standard deviation. The

material properties are comparable to previously-measured small-strain regime properties of human vocal fold tissues.^{26,27}

The rheological test results are shown in Figure 4. Again, not all models could be made simultaneously so the mean and standard deviation of each layer are shown. Both the elastic and viscous shear moduli (G' and G'' , respectively) increased with increasing frequency, demonstrating the viscoelastic characteristics of the materials. These followed a similar trend of increasing shear and viscous shear moduli with increasing angular frequency found in human vocal fold tissue.^{26,27}

Injections—As shown in Figure 5, the bowed model mounting plates allowed for injection of material after pre-injection vibratory data was acquired. The injections were placed at the lateral margin of the body using a 500 μ L syringe (SY133500, Hamilton Company) and hypodermic needle (1.5 in, 22 gauge, 305156, Becton, Dickinson & Co). The injection experimental protocol is discussed in more detail below in the Experimental Procedure section.

An addition-cure silicone injection material was chosen that had material properties comparable to two materials, Radiesse[®] and Cymetra[®], that are currently used in vocal fold augmentation surgery.²⁸ The material consisted of one part A of Ecoflex[®] 0030, one part B of Ecoflex[®] 0030, and two parts Silicone Thinner (all products manufactured by Smooth-On, Inc.; parts were measured by weight). A cure accelerant (Plat-Cat, Smooth-On, Inc.) was added by weight (10%) to Ecoflex[®] part A and mixed thoroughly before adding to part B. Figure 6 shows a comparison of the rheological properties of the injected material with Radiesse[®] and Cymetra[®].

Experimental Setup

Two configurations were used in this experiment: a full larynx configuration, in which a normal model was paired with a bowed model, and a hemilarynx configuration with a single bowed model. The full larynx setup was used to acquire pre- and post-injection onset pressure, frequency, flow rate, open quotient, and glottal gap high-speed imaging data. The hemilarynx setup was used to track pre- and post-injection medial surface motion.

Full Larynx Configuration—The full larynx setup is shown in Figure 7. Pressurized air entered an expansion chamber, followed by a 0.95 cm-diameter, 50 cm-long flexible PVC tube that was rigidly held in place. Air flow was regulated by means of a manual valve and measured with a rotameter-type flow meter (Key Instruments, FR4A37BVB). Prior to injection each bowed model and mounting plate assembly was paired with a normal model and mounting plate assembly. The pairing was accomplished by screwing the mounting plates together such that the medial surfaces nearly touched in the absence of flow. The plates were mounted at the end of the PVC tube. Mean subglottal pressure was acquired approximately 3 cm upstream of the vocal fold models with a differential pressure transducer (Omega PX 138-001D5V) and a National Instruments system (PXI-1042Q) using LabVIEW programming.

A digital high-speed camera (Photron SA3) was positioned approximately 13 cm above the model and acquired images at 3000 frames per second with a 1/6000 s shutter speed and 512×512 pixel resolution. The camera was fitted with a 50 mm lens (AF Nikkor) and a 20 mm extension tube (AF Zeikos Macro). Four high-intensity LED lights (Visual Instrumentation Corporation #900415, controller #200900) illuminated the image area. High-speed images were acquired at 110% and 120% of each model's respective onset pressure. The open quotient was estimated by dividing, over one period, the number of

images showing glottal closure at the approximate anterior-posterior midplane by the total number of images spanning one period.

Hemilarynx Configuration—A hemilarynx configuration, consisting of a single model vibrating against a clear acrylic plate (Figure 8), was used to track bowed model medial and inferior surface motion in a manner similar to that which has been done previously using excised larynges.^{29,30} Two synchronized high-speed cameras (Photron SA3), each using the same lens hardware and image acquisition settings as in the full larynx experiments, were used to acquire stereo images of the model during vibration.

Medial surface tracking was accomplished as follows; further details can be found in Murray.³¹ A grid of 25 black dots was applied to the medial and inferior surfaces of the model using a Sharpie® Ultra-Fine-Point marker as shown in Figure 9. The point locations were extracted using a hybrid manual/cross-correlation custom code in MATLAB. The point locations in the images were then transformed to three-dimensional coordinates using a direct linear transformation (DLT).^{31–33} From time histories of the point locations, mucosal wave velocity and phase delay were calculated using the method described by Titze et al.³⁴

Experimental Procedure

For the full larynx experiments, three models with 10% bowing and three models with 20% bowing were each paired with a separate normal model. Each model pair was brought to its onset pressure five times and the mean determined. Each model pair was then vibrated at 110% and 120% of its mean onset pressure, during which frequency, flow rate, and high speed image data were taken. Uncertainty estimates for each measurement are listed in Table 3. Detailed calculations can be found in Murray.³¹

After the above pre-injection data had been acquired, the bowed model was injected with various amounts of silicone to achieve one of three degrees of glottal closure: “sufficient” (just enough to close the glottal gap), “insufficient” (not enough to close the glottal gap), and “excess” (more than enough to close the glottal gap). For the sufficient injections, material was injected until the entire glottal gap appeared to be closed when viewed from above. For the insufficient injections, material was injected until the gap between the normal and bowed medial surfaces began to close. For the excess injections, material was first injected until the glottal gap was closed, and then additional material was injected until the medial surface of the bowed model was convex and compressed against the normal model (Figure 10). The average volume and standard deviation of the injected material quantities for each injection location are listed in Table 4. These volumes are similar to injection amounts of various substances ranging from approximately 0.2 mL to 6 mL used in clinical studies.^{35–38}

After injection of a bowed model, the mounting plate assembly was removed from the test setup so that tests using other models could be performed while the injected silicone cured. Curing time was approximately 1.5 hours. After curing and remounting on the test setup, the same measurements that had been performed pre-injection were repeated.

The process described above was repeated three times to test three specimens of both 10% and 20% bowing for each injection case; however, for two cases, the 10% excess and 20% sufficient injection cases, only two data sets were usable due to flawed augmentation injections. A similar process was used for the hemilarynx case, although only one experiment was performed for each injection case.

RESULTS AND DISCUSSION

Onset Pressure

Figure 11 shows the mean and standard deviation of the onset pressures for all full larynx experiments. In 12 of the 16 injection cases, the onset pressure decreased after injection, which corresponds well with pre- and post-operative subglottal peak pressure measurements from clinical studies of the medialization laryngoplasty procedure.³⁹ This decrease in onset pressure was attributed to a reduction in pre-vibratory glottal gap. It is noted that subsequent inspection of the models revealed that in all cases where the onset pressure increased, the injection was found to have been in a more superior location in the model, although the consequence of this would need further study. The effect of the augmentation injections was generally more pronounced for the 20% than for the 10% bowing cases.

Regarding the physical mechanisms contributing to this observed change in onset pressure, as well as changes in the other metrics discussed below, it has been shown that the vibratory responses of synthetic vocal fold models are sensitive to changes in both geometry and material properties of the individual layers.^{40–41} As the injections were placed in these models, both geometry and stiffness distribution characteristics were altered. Further investigations are required to quantify the factors that influenced the models' flow-induced responses discussed here. In general, however, the change in responses seen in these models were likely due to model alterations such as pre-vibratory intraglottal angle, changes in the inferior entrance angle, thickness of the lamina propria layer, and induced stresses in the lamina propria layer.

Glottal Flow Rate

As shown in Figure 11, the flow rate generally decreased between pre- and post-injection, likely due to the reduction of glottal area and vibration amplitude caused by the injections. The most significant reduction in flow rate was seen in the 20% bowed model. This correlates well with clinical studies. In their study of five patients undergoing augmentation injections with hydroxylapatite, Rosen and Thekdi³⁷ showed a reduction of glottal flow rate from 114–803 mL/s to 134–409 mL/s. Umeno et al.⁴⁰ showed pre- and post-operative flow rates of 239–558 mL/s and 125–279 mL/s, respectively, from fat injection laryngoplasty (64 patients).

Open Quotient

The average pre-injection open quotient for all models was approximately one (Figure 11), showing there was little to no glottal closure. After the injections were placed, the amount of glottal closure was closer to values found during human phonation.⁴² Three of the insufficient injection cases did not show improvement in open quotient because the injections never closed the glottal gap.

Vibration Frequency

The injections increased vibratory frequency in 14 of 16 cases, as can be seen in Figure 11. This trend in increased frequency is opposite clinical results from a study of patients undergoing either medialization laryngoplasty or augmentation injection procedures using autologous fat or calcium hydroxylapatite (CaHA).⁴³ Further studies are necessary to quantify the factors causing this frequency discrepancy. The general increase in frequency was attributed to the additional injected material effectively increasing the body and cover stiffness, which in turn increased the natural frequency of the model. Subsequent inspection of the models revealed that the two cases which exhibited a decrease in vibration frequency had injections that were located more inferiorly than the other models' injections.

Statistical Analysis

Analysis was performed to determine the degree of statistical significance of the pre- and post-injection changes in onset pressure, glottal flow rate, open quotient, and vibration frequency. An F-test of the data showed that the assumption of equal variances was adequate. Therefore, a two-sample t-test for group means with equal variance was performed with $\alpha = 0.05$ (95% confidence). The results are shown in Table 5.

Two overall observations can be seen. First, no parameters for the insufficient case were statistically significant. Although the general trends in the data for the insufficient injection case shown in Fig. 11 correlate with those for the sufficient and excess injection conditions, the variation in the data is too large to determine statistical significance. This suggests that for the vocal fold models used in this study, achieving statistically significant changes in model responses requires a sufficient volume of material to close the glottal gap.

The second overall observation is that no statistical significance was found for the onset pressure metric in any injection case. Possible reasons for this could be the small magnitude of pre- and post-injection onset pressure responses, potential variations in vertical placement of the injected material, and tackiness of the medial surface, any of which could act as a potential confounding effect. Adjustments could be made to mitigate these external effects. For example, although the pre- and post-injection onset pressure change is small, statistical significance could be more easily determined using a larger sample size. A better method of controlling the vertical placement may also reduce the variability in onset pressure. Further studies with a larger sample size and tighter control over the possible confounding effects are warranted.

Superior Surface Imaging

Figure 12 shows superior surface images for one period of oscillation, pre- and post-injection, for the 20% bowed, excess injection case vibrating at 120% onset pressure. Before injection there was incomplete glottal closure and asymmetry in the vibration pattern. After injection glottal closure was achieved. Due to post-injection asymmetric material properties and geometry, the vibration pattern remained asymmetric, with the normal model having the greater amplitude.

Medial Surface Tracking

The hemilarynx configuration was used to investigate the effect of injections on the medial surface motion. Calculated data included marker trajectories, vertically-propagating wave speed, and intraglottal profile phase angle. Figure 13 shows the trajectory of the points on column C3 (refer to Figure 9) through one period of oscillation, pre- and post-injection, for the 20% bowed, excess injection case vibrating at 110% of onset pressure. For reference, the subplots in the first frame of each case show the associated uncertainty envelope for one marker (see Murray³¹ for details). It can be seen that even though the model was bowed, there was still an alternating convergent-divergent profile of the medial surface during vibration. Mucosal wave-like motion is also evident. However, the trajectories clearly show that the glottis was open during the entire oscillation cycle. Notably, the post-injection trajectories showed bulging of the inferior surface due to the location of the injection. The medial surface still alternated between a convergent and a divergent profile and the mucosal wave-like motion was still observed, although the amplitude of vibration was reduced.

Column C3 was used to monitor changes caused by the injections on wave velocity and phase difference. Table 6 shows that the injections decreased the wave velocity and increased the phase difference by an average of 0.5 mm/s and 12°/mm, respectively. The experimental results for both pre- and post-injection wave velocity and phase delay were

comparable to the wave velocity (0.5 m/s – 2.2 m/s) and phase delay (27°/mm – 61°/mm) values reported by Titze et al.³⁴

CONCLUSIONS

Synthetic, self-oscillating vocal fold models were created which simulated vocal fold bowing via reduction of the volume of the body layer from that of a normal model. The models vibrated with mucosal wave-like motion and at onset pressures and frequencies typical of human phonation. To explore the influence of injections on bowed model responses, three different amounts of injections were placed in models with 10% and 20% bowing: sufficient to close the glottal gap, insufficient to close the glottal gap, and excess injection to cause convexity of the bowed model. The models showed a general pre- to post-injection decrease in onset pressure, glottal flow rate, and open quotient, together with a corresponding increase in vibration frequency.

Hemilarynx configuration experiments showed a general decrease in wave velocity and increase in phase delay. It has been shown that a decrease in mucosal wave velocity corresponds to a decrease in phonation effort in human vocal folds.^{44,45} From these results, it may thus be inferred that the injections decreased the mechanical “effort” required to vibrate the models, thus correcting for the adverse consequences of the pre-injection bowing and glottal incompetence, although further investigations into this are certainly warranted.

The model was successfully altered to exhibit various degrees of bowing, which were then mitigated by injecting material. Clearly the model and procedures were idealizations. Further, the simulations only allow for investigation of the flow-induced vibratory physics, absent physiological, tissue-specific responses to injected materials. Migration of injected material would be different in real tissue. Because of this, the results are specific to the vocal fold models, and further excised larynx and/or clinical studies should be performed in order to obtain a complete understanding of the effects of augmentation injections on human vocal fold vibration. Consequently, the contribution of the present study is not one with direct clinical implication, but rather a methodology which may be used in future studies aimed at exploring isolated physical phenomena associated with augmentation, and perhaps other phonosurgical, procedures. For example, the model could be extended to study the mechanical effects of other simulated pathologies, such as sulcus vocalis, cysts, changes in material properties due to aging, and the effect of medialization laryngoplasty compared to augmentation injections. Additional physical measures that were not evaluated in this research that the model could be used to study are the effect of the bowing and the augmentation injections on subglottal and supraglottal flow, flow resistance, and vocal efficiency.

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FIGURE 1.

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

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.

FIGURE 3.

Superior view of normal (left) and bowed (right) vocal fold models showing bowing definition. Flow direction is out of the page. Epithelium and fiber not shown.

FIGURE 4.

Elastic shear modulus (G' , left) and viscous shear modulus (G'' , right) for the four layers used in the models, as well as data for the human cover from Chan and Rodriguez.²⁷ Error bars show one standard deviation.

FIGURE 5. Mounting plate with holes for injecting material laterally into the bowed models. Flow direction is from inferior to superior.

FIGURE 6.

Elastic (left) and viscous (right) shear moduli of the silicone injected material with two injections commonly used in augmentation surgery. ●: injected material; ■: Cymetra®, and ◆: Radiesse® (the latter two data sets courtesy Caton et al.²⁸).

FIGURE 7.
Full larynx configuration experimental setup (not to scale).

FIGURE 8.
Hemilarynx configuration experimental setup (not to scale).

FIGURE 9.

Image from one high-speed camera of the medial and inferior surfaces of the synthetic vocal fold model in the hemilarynx configuration. Ink dots for point-tracking purposes are visible. Columns and rows are indexed as C1-C5 and R1-R5, respectively.

FIGURE 10. Superior view of paired models pre-injection (left image) and post-injection (right image).

FIGURE 11.

Pre- and post-injection data for sufficient, insufficient, and excess injections. Left three columns are from the 10% bowing cases; data from the 20% bowing cases are in the right three columns. Solid, dashed, and dotted lines denote experiments with different models. Error bars in the onset pressure data denote one standard deviation.

Pre-Injection ($p_{\text{sub}} = 0.43 \text{ kPa}$) **Post-Injection ($p_{\text{sub}} = 0.38 \text{ kPa}$)** **FIGURE 12.**

Timeline of one cycle of oscillation for the 20% bowed, excess injection cases, pre- and post-injection, while vibrating in response to a subglottal pressure of 120% of the respective onset pressure. In each figure the left and right vocal fold models are normal and bowed, respectively.

Pre-Injection ($p_{\text{sub}} = 0.66$ kPa) **Post-Injection ($p_{\text{sub}} = 0.63$ kPa)** **FIGURE 13.**

Pre-injection (top) and post-injection (bottom) trajectories of the ink dots (here shown as filled circles) in column C3 (see Fig. 9). Frames from left to right correspond to successive phases of one cycle. Horizontal and vertical axes correspond to medial-lateral and inferior-superior orientations, respectively (units of mm). Each solid line is an approximate fit to the ink dot locations and thus shows the approximate medial surface profile. The vertical dotted line represents the location of the clear acrylic plate. Flow is from bottom to top. The inset figures show the uncertainty associated with point selection determination.

TABLE 1

Geometric parameters and description used to define model

Parameters	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

TABLE 2

Young's modulus for each layer of the synthetic model (standard deviation shown in parentheses)

Model Section	Modulus (kPa)
Body	11.82 (1.05)
Ligament	1.63 (0.90)
Epithelium	49.78 (4.15)
Injection	12.62 (6.86)

TABLE 3

Measurement uncertainty estimates

Metric	Uncertainty
Open Quotient	± 0.047
Subglottal Pressure	± 35 Pa
Onset Pressure	± 64 Pa
Glottal Flow Rate	± 43 mL/s
Point Location	± 0.28 mm

TABLE 4

Average injection amounts (μL) for symmetric and hemilarynx experiments (standard deviation shown in parentheses). “Left,” “center,” and “right” refer to the three centermost injection holes in the mounting plates (see Figure 5).

Case	Left	Center	Right
10% Sufficient	63.6 (15.28)	96.7 (5.77)	50 (10.2)
10% Insufficient	0	60 (17.32)	0
10% Excess	150 (11.2)	140 (14.14)	95 (77.8)
20% Sufficient	100 (42.4)	230 (141)	100 (14.1)
20% Insufficient	50 (10.3)	110 (36.1)	0
20% Excess	115 (21.2)	316 (28.9)	120 (30.0)

TABLE 5

Statistical significance of measured factors ($p = 0.05$).

Factor	10% Bowing			20% Bowing		
	Sufficient	Insufficient	Excess	Sufficient	Insufficient	Excess
Onset Pressure	No	No	No	No	No	No
Flow Rate	No	No	Yes	Yes	No	Yes
Open Quotient	Yes	No	Yes	Yes	No	Yes
Frequency	Yes	No	Yes	Yes	No	Yes

TABLE 6

Wave velocities and phase delays of column three (C3, see Figure 9) for the 10% and 20% bowing cases. Numbers before and after arrows denote pre- and post-injection quantities, respectively. Data were obtained with each model vibrating at 110% of its respective onset pressure.

Case	Wave velocity (m/s)	Phase delay (°/mm)
10% Sufficient	1.41 → 1.14	31.5 → 38.3
10% Insufficient	1.23 → 0.98	32.9 → 43.0
10% Excess	1.18 → 1.02	30.9 → 40.9
20% Sufficient	1.31 → 1.02	27.2 → 44.6
20% Insufficient	2.37 → 1.85	15.6 → 24.5
20% Excess	3.00 → 1.87	12.9 → 22.0