Biomechanical Flow Amplification Arising From the Variable Deformation of the Subglottic Mucosa

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Summary: Objective. This study mapped the variation in tissue elasticity of the subglottic mucosa, applied these data to provide initial models of the likely deformation of the mucosa during the myoelastic cycle, and hypothesized as to the impact on the process of phonation.

Study Design. Six donor human larynges were dissected along the sagittal plane to expose the vocal folds and subglottic mucosa. A linear skin rheometer was used to apply a controlled shear force, and the resultant displacement was measured. These data provided a measure of the stress/strain characteristics of the tissue at each anatomic point. A series of measurements were taken at 2-mm interval inferior of the vocal folds, and the change in elasticity was determined.

Results. It was found that the elasticity of the mucosa in the subglottic region increased linearly with distance from the vocal folds in all 12 samples. A simple deformation model indicated that under low pressure conditions the subglottic mucosa will deform to form a cone, which could result in a higher velocity, thus amplifying the low pressure effect resulting from the Venturi principle, and could assist in maintaining laminar flow.

Conclusions. This study indicated that the deformation of the subglottic mucosa could play a significant role in the delivery of a low pressure airflow over the vocal folds. A large scale study will now be undertaken to secure more data to evaluate this hypothesis, and using computational fluid dynamics based on actual three-dimensional structure obtained from computed tomography scans the aerodynamics of this region will be investigated.

Key Words: Vocal folds–Phonation–Biomechanics–Tissue deformation–Aerodynamics.

INTRODUCTION

The principles underlying the ability to phonate are now well established.[1] The purpose of this study was to focus on the tissue structures in the subglottic region that are less well studied. Previous studies[2,3] indicated that the stiffness of subglottic mucosa in pig and canine larynges increased with distance inferior from the vocal folds. The objective of this study was to determine if human tissue exhibited the same variation. To achieve this, the team deployed a linear skin rheometer (LSR), as used in comparable studies by other teams who were examining the elastic properties of vocal fold tissue.[4,5]

Our reason for examining this region is that although the subglottic region is rarely studied due to the difficulty in visualization, some studies have indicated that it may play a role in phonation, and that scarring in this region could affect the quality of voice. Sundberg[6] identified that there are mechanoreceptors in this region that are used to sense the transfer of energy from the subglottal airflow into the vocal folds in advance of the mucosal wave. Smith[7] examined the change in pitch in 14 female patients (mean age: 53) following a cricotracheal resection. In all cases, the mean fundamental frequency fell significantly, typically by 21 Hz. Both studies indicate that the subglottal region does play a role in phonation, and this study was devised to gain a better understanding of how that region functions during phonation, and to see if the biomechanics could explain these reported impacts.

Having obtained the results, which indicated that the mucosa does exhibit a gradation in stiffness, the manner in which this structure will deform during the low pressure phase of the myoelastic cycle was modeled using a simple deformation model. The impact of the deformed structure is considered with respect to how it would affect the aerodynamics of the airflow in this region. This simplistic analysis indicated that the end result is that the flow rate would be increased, possibly magnifying the extent of vocal fold closure, and could assist laminar flow.

MATERIALS AND METHODS

Six excised larynges were used for this study, three male and three female. All were obtained in accordance with approved ethical principles. They were obtained from mortuary cases, and then deep-frozen before gradual thawing and use; all were stored for many months before use. The larynges were hemisected to reveal the vocal folds and subglottic mucosa, providing the study with 12 sample hemi-larynges. These samples were mounted on a three-axis micrometer-controlled table. An LSR adapted for use with soft tissues was deployed for this study. The LSR has been deployed in a range of previous studies that examined the variation in vocal fold biomechanics with respect to anatomic position and direction of applied stress.[4,5] The current experimental setup has been enhanced as a result of the experiences gained from deploying the LSR in these earlier studies, as shown in Figure 1. A glass cannula with a 90° bend was used to apply a tangential force to the epithelium, and was attached using a suction pressure of 50 mbar. The LSR delivered a controlled cyclical force of ± 1 g to the attachment point and the displacement was logged. From these data, a regression algorithm provides a best fit to the pair of sine waves, which provide a measure of the stress/strain characteristics in terms of grams force per millimeter displacement. Although it is possible to convert these

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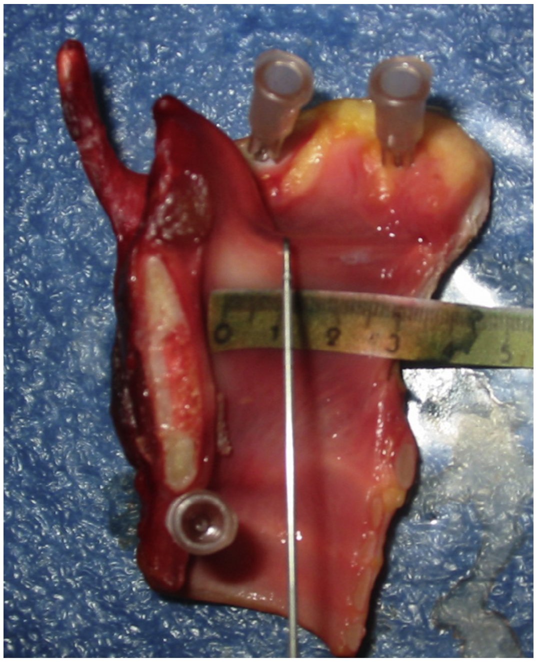

FIGURE 1. Typical experimental setup showing exposed hemi-larynx and measurement probe.

readings into estimates of shear modulus using established methods based on the geometry of the experimental setup, we are only interested in the change in elastic properties. Therefore, the results are presented in g/mm unit, and the graphical representations are normalized with respect to the stiffness of the vocal folds in order to present the change of stiffness of the mucosa with respect to vocal fold stiffness.

Ten readings were taken at each sample point and were averaged to obtain a series of point-specific readings with respect to anatomic context, being the distance inferior from the vocal folds.

The calculations carried out made use of the following established formulae.

The change in pressure arising from laminar flow through a constriction is given in Equation 1. This was used to calculate the drop in air pressure in the region near the vocal folds.

$$\Delta P = \rho / 2 \times \left(V1^2 - V2^2\right) \quad (1)$$

where ΔP is the change in pressure within the constricted flow region; ρ is the density of air; V1 is the airflow velocity before the constriction; and V2 is the airflow velocity within the constriction.

Young modulus for linear extension is given in Equation 2 and was used to model the mucosal deformation.

$$l = F / \left(L \times A \times Y\right) \quad (2)$$

where l is linear extension; F is the uplift force; L is the initial length of the material; A is the surface over which the uplift force is applied; and Y is Young modulus.

To develop the next stage of the study, which is modeling the aerodynamics of this region, a computed tomography (CT) scan of a human larynx was converted to provide a three-dimensional (3D) model based on the actual anatomic structure for use with a computational flow dynamics (CFD) program. CT images of the excised larynges have been used to create 3D reconstructions with the help of an open-source medical imaging software, *3D Slicer* (http://www.sci.utah.edu/cibc-software/seg3d.html; The Center for Integrative Biomedical Computing, University of Utah). This model will be used to determine the changes in the aerodynamics that arise when the subglottic mucosa is deformed under low pressure in the next stage of this research program.

RESULTS

Table 1 shows the raw results. The keys for the donor column are the following: M for male, F for female, age of donor, L for left, and R for right side. The first column is the measurement

TABLE 1.
Stress/Strain Characteristics From All 12 Hemi-Larynges With Respect to Distance Inferior From the Vocal Fold

Donor Male (M) or Female (F), Age, Left (L) or Right (R)	Distance Inferior From the Vocal Folds							Quality Indices	
	Vocal Folds	2 mm	4 mm	6 mm	8 mm	10 mm	12 mm	Coefficient of Variance (%)	Correlation Coefficient Left Versus Right
F, 63, L	0.44	0.52	0.53	0.63	0.59	0.65	0.72	14	
F, 63, R	0.36	0.42	0.45	0.51	0.56	0.65	0.55	15	0.86
F, 74, L	0.44	0.52	0.49	0.53	0.53	0.62	0.64	12	
F, 74, R	0.33	0.42	0.46	0.48	0.49	0.58	0.63	9	0.96
F, 67, L	0.15	0.17	0.19	0.22	0.26	0.28	0.28	4	
F, 67, R	0.13	0.17	0.19	0.2	0.24	0.27	0.24	6	0.97
M, 57, L	0.57	0.53	0.64	0.68	0.7	0.69	0.65	13	
M, 57, R	0.34	0.39	0.47	0.45	0.57	0.6	0.6	8	0.78
M, 85, L	0.37	0.5	0.58	0.72	0.74	0.65	0.62	15	
M, 85, R	0.37	0.48	0.51	0.55	0.56	0.66	0.69	11	0.71
M, 68, L	0.32	0.41	0.44	0.45	0.48	0.53	0.62	14	
M, 68, R	0.35	0.4	0.45	0.44	0.51	0.49	0.57	14	0.96

Units are g/mm.