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Effect of Resection Depth of Early Glottic Cancer on Vocal Outcome: An Optimized Finite Element Simulation

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Objectives/Hypothesis: To test the hypothesis that subligamental cordectomy produces superior acoustic outcome than subepithelial cordectomy for early (T1–2) glottic cancer that requires complete removal of the superficial lamina propria but does not involve the vocal ligament.

Study Design: Computer simulation.

Methods: A computational tool for vocal fold surgical planning and simulation (the National Center for Voice and Speech Phonosurgery Optimizer-Simulator) was used to evaluate the acoustic output of alternative vocal fold morphologies. Four morphologies were simulated: normal, subepithelial cordectomy, subligamental cordectomy, and transligamental cordectomy (partial ligament resection). The primary outcome measure was the range of fundamental frequency (F_0) and sound pressure level (SPL). A more restricted F_0-SPL range was considered less favorable because of reduced acoustic possibilities given the same range of driving subglottic pressure and identical vocal fold posturing.

Results: Subligamental cordectomy generated solutions covering an F_0-SPL range 82% of normal for a rectangular vocal fold. In contrast, transligamental and subepithelial cordectomies produced significantly smaller F_0-SPL ranges, 57% and 19% of normal, respectively.

Conclusion: This study illustrates the use of the Phonosurgery Optimizer-Simulator to test a specific hypothesis regarding the merits of two surgical alternatives. These simulation results provide theoretical support for vocal ligament excision with maximum muscle preservation when superficial lamina propria resection is necessary but the vocal ligament can be spared on oncological grounds. The resection of more tissue may paradoxically allow the eventual recovery of a better speaking voice, assuming glottal width is restored. Application of this conclusion to surgical practice will require confirmatory clinical data.

Key Words: glottic cancer, vocal cord cancer, vocal fold cancer, cordectomy, functional morphology, voice range profile, multiobjective optimization, patient-specific simulation, voice simulation, optimized simulation, NCVS simulator.

Level of Evidence: N/A.

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INTRODUCTION

Voice outcome of surgical treatment for early (T1–2) glottic cancer is an important measure because the oncologic result is equivalent between surgery and radiation,[1–6] leaving functional outcome often an important consideration when choosing the treatment modality. The postoperative voice is generally poorer with deeper resection,[7–15] which is consistent with greater glottal insufficiency due to tissue loss. However, new data challenge the universality of this trend. Hillel et al.[16] reported that patients who underwent subligamental cordectomy had better postoperative voice and stroboscopy scores than those who underwent subepithelial cordectomy. The authors concluded that if the tumor extends most of the thickness of the superficial layer of the lamina propria (SLLP) such that minimal SLLP can be preserved, the vocal ligament should be resected even if it is not oncologically necessary. This suggestion runs counter to conventional teaching of vocal fold microsurgery, which emphasizes the preservation of nondiseased tissue in order to maximally preserve phonatory function. However, those findings echoed the experience of other surgeons who have had surprisingly good vocal outcomes from subligamental cordectomies.[17]

Comparing voice outcomes between subepithelial cordectomy that removes the entire SLLP and subligamental cordectomy is intrinsically challenging for several reasons. First, the comparison requires a specific subset of early glottic cancers, namely those that extend close to but do not involve the vocal ligament, for which

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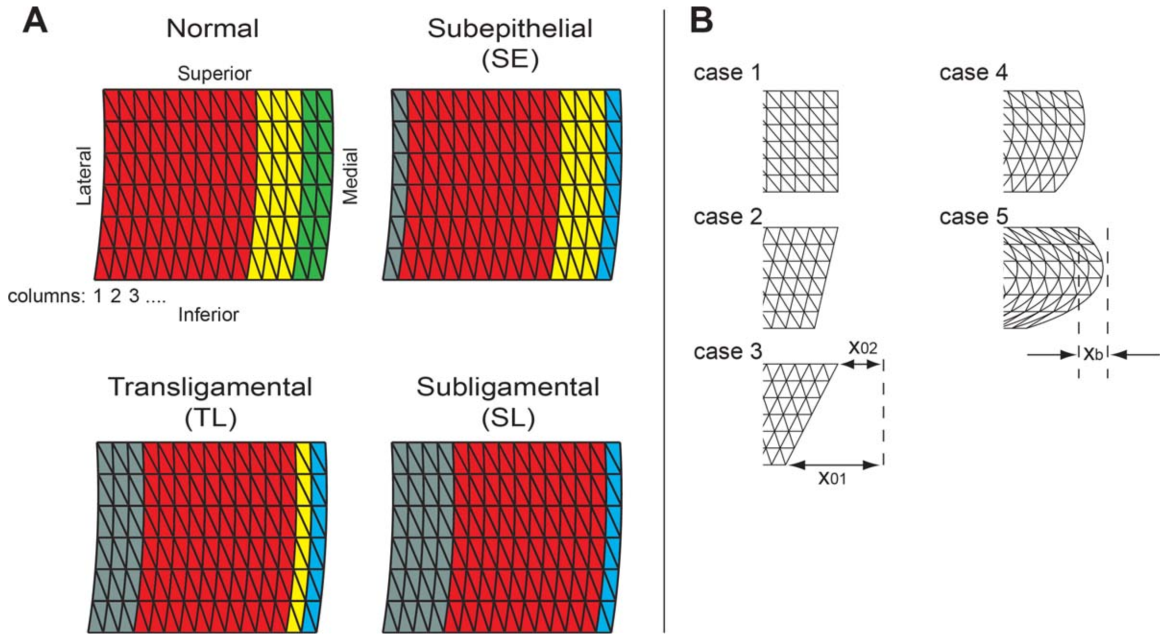

Fig. 1. (A) The vocal fold finite element model consisted of 15 columns representing three or four different layers. The normal vocal fold consisted of a muscle layer (red; 10 columns), ligament (yellow; 3 columns), and SLLP (green; 2 columns). Three excisions were modeled: Subepithelial cordectomy (SE), transligamental cordectomy (TL), and subligamental cordectomy (SL). In all three surgeries, a layer of scar is modeled (blue; 1 column). The remaining vocal fold tissue was medialized with an inelastic implant (gray) to maintain prephonatory glottal width. (B) Five vocal-fold medial surface shapes were tested (case 1: rectangular; case 2: convergent; case 3: 2X convergent; case 4: convergent + bulging; case 5: 2X convergent + bulging). The convergence parameters X_{01}, X_{02},and bulging parameter X_b, are specified in Table I.

either surgical option is oncologically sound. These tumors are not rare but are still uncommon enough that it is difficult for a study to accumulate large numbers of them. For example, only four patients were in the subepithelial cordectomy group in Hillel et al.[16] Second, scarring following subepithelial or subligamental cordectomy is known to be highly variable.[18] Third, there is substantial variability in vocal fold tissue structure and acoustic output even among normal subjects.[19–21] To overcome these individual variations, an impractically large sample size would be required.

Computer simulation of vocal fold vibratory behavior can provide insight into clinical observations.[22,23] Finite-element and finite-difference approaches have been reported over the past decade.[24–27] Simulation has been used for planning medialization laryngoplasty,[28] for example. The goal of this study is to assess the relative acoustic merits of subepithelial cordectomy and subligamental cordectomy utilizing a new computational approach combining finite element model (FEM) voice simulation[29] with multiobjective optimization.[30] A voice simulator produces one set of acoustic output variables, given a defined input vocal fold geometry and a fixed subglottal pressure. A meaningful comparison between two different vocal fold geometries should entail a *range* of possible acoustic outputs, given a clinically relevant range of subglottal pressures for each geometry. Therefore, a fair comparison requires thousands of simulation runs. To do this efficiently, a multiobjective optimization algorithm is coupled to the simulator to fully explore the range of possible acoustic outputs, an approach implemented in the National Center for Voice and Speech (NCVS) Phonosurgery Optimizer-Simulator.[30] In this study, the primary acoustic outcomes are the ranges of fundamental frequency (F_0) and sound pressure level (SPL). F_0 and SPL are of interest because they are fundamental acoustic parameters that characterize a voice. The ranges of F_0 and SPL determine a speaker's pitch range and loudness. Secondary simulation outcome variables are a physiological input parameter (subglottal pressure) and an output parameter (phonation onset time). We hypothesize that subligamental cordectomy produces a greater F_0-SPL range than subepithelial cordectomy.

MATERIALS AND METHODS

Finite-Element Models

Each vocal fold was modeled in three layers in the NCVS simulator: SLLP, ligament, and muscle. The SLLP layer was taken to represent SLLP plus epithelium, which was not explicitly modeled. Future work will include the epithelium as a discrete layer. Tissue was divided into triangular elements in the coronal plane and into rectangular layers in the anterior–posterior direction, along the length of the vocal fold. The FEM consisted of 15 vertical columns from lateral to medial, six horizontal layers from superior to inferior, and five anterior–posterior layers (Fig. 1A). Each layer (SLLP, ligament, and muscle) was represented by several columns of elements, with mechanical properties common to the elements within that morphological layer (Table I). Based on layer thickness in published

TABLE I.

Ranges of objective functions (F_0, SPL) and decision variables (μ_1, subglottal pressure) used for optimized simulation. Other parameters were kept constant. Three surgeries were simulated (Fig. 1). The subscripts denote the layer specified (layer 1: normal SLLP or scar; layer 2: ligament; layer 3: muscle; layer 4: implant). The material in the FEM was considered as a fiber-gel compound, fiber-like along the vocal fold longitudinally but gel-like in the coronal plane (i.e., transversally isotropic). The longitudinal shear moduli of SLLP, ligament, and muscle were designated as μ_1', μ_2', and μ_3', respectively. The transverse shear moduli of SLLP, ligament, and muscle were designated as μ_1, μ_2, and μ_3, respectively, and reflect the gel properties. Viscosity is designated by η_1, η_2, and η_3. For the scar layer, μ_1' would increase with greater deposition of organized collagen in the longitudinal orientation. Because collagen fibers are randomly organized in scar,[45] μ_1' was not altered. The lower boundary of μ_1 was increased three-fold to account for the higher collagen fiber content in scar. This was based on the observation that scarred vocal fold tissue demonstrates a smaller range for μ, with an increased lower limit.[46]

	Normal Vocal Fold	Subepithelial	Transligamental	Subligamental
F_0 (Hz)	120 (90–150)	120 (90–150)	120 (90–150)	120 (90–150)
SPL (dB)	70 (60–80)	70 (60–80)	70 (60–80)	70 (60–80)
Subglottal pressure (kPa)	0.01–2	0.01–2	0.01–2	0.01–2
μ'_1 (dyn/cm^2)	5,000	5,000	5,000	5,000
μ'_2 (dyn/cm^2)	20,000	20,000	20,000	n/a
μ'_3 (dyn/cm^2)	15,000	15,000	15,000	15,000
μ'_4 (dyn/cm^2)	n/a	500,000	500,000	500,000
μ_1 (dyn/cm^2)	5,000–50,000	15,000–50,000	15,000–50,000	15,000–50,000
μ_2 (dyn/cm^2)	5,000	5,000	5,000	n/a
μ_3 (dyn/cm^2)	5,000	5,000	5,000	5,000
μ_4 (dyn/cm^2)	n/a	500,000	500,000	500,000
η_1 (poise)	2	2	2	2
η_2 (poise)	2	2	2	n/a
η_3 (poise)	2	2	2	2
η_4 (poise)	n/a	50	50	50
Case 1: Rectangular				
VF convergence (cm)	$x_{01} = 0.03$	$x_{01} = 0.03$	$x_{01} = 0.03$	$x_{01} = 0.03$
	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$
VF bulging (cm)	0	0	0	0
Case 2: 1X convergent				
VF convergence (cm)	$x_{01} = 0.06$	$x_{01} = 0.06$	$x_{01} = 0.06$	$x_{01} = 0.06$
	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$
VF bulging (cm)	0	0	0	0
Case 3: 2X convergent				
VF convergence (cm)	$x_{01} = 0.12$	$x_{01} = 0.12$	$x_{01} = 0.12$	$x_{01} = 0.12$
	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$
VF bulging (cm)	0	0	0	0
Case 4: 1X convergent with bulging				
VF convergence (cm)	$x_{01} = 0.06$	$x_{01} = 0.06$	$x_{01} = 0.06$	$x_{01} = 0.06$
	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$
VF bulging (cm)	0.03	0.03	0.03	0.03
Case 5: 2X convergent with bulging				
VF convergence (cm)	$x_{01} = 0.12$	$x_{01} = 0.12$	$x_{01} = 0.12$	$x_{01} = 0.12$
	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$	$x_{02} = 0.03$
VF bulging (cm)	0.07	0.07	0.07	0.07

F_0 = fundamental frequency; FEM = finite element model; SLLP = superficial layer of the lamina propria; SPL = sound pressure level; VF = vocal fold.

histologic images,[31] the most medial two columns were designated as the SLLP, the next three columns as the ligament, and the lateral 10 columns as the muscle in a normal vocal fold model (Fig. 1A). The critical viscoelastic parameters for each tissue column are μ, the shear modulus in a plane transverse to the fibers; μ', the shear modulus in a plane that includes the fibers and their longitudinal tensions; and η, the viscosity. The Young's modulus in the transverse plane is dependent on μ, and

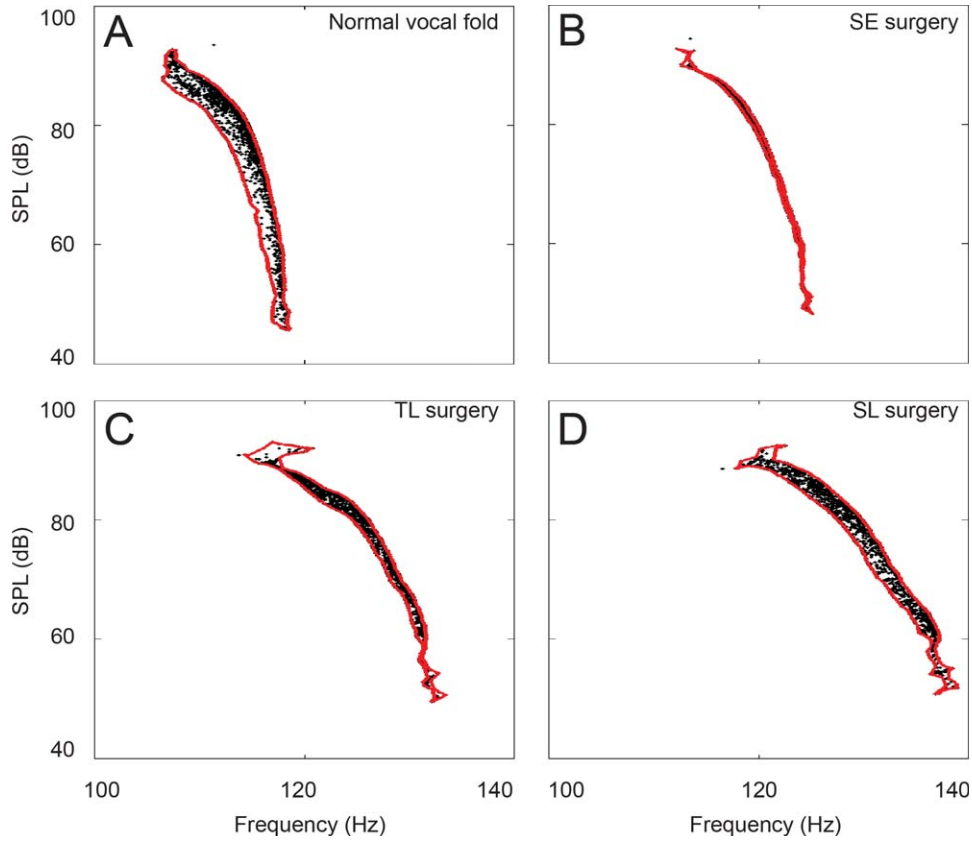

Fig. 2. Four sets of solutions spread in the F_0-SPL space, each representing the acoustic output of a particular surgical morphology: (A) normal; (B) subepithelial cordectomy (SE); (C) transligamental cordectomy (TL); and (D) subligamental cordectomy (SL). The red outline shows the area covered by the respective set of solutions in F_0-SPL space. The outline was estimated by a nonconvex hull using Delaunay triangulation. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

therefore does not need separate specification.[29] Subscripts on these parameters define the tissue layer.

To simulate the postoperative vocal fold anatomy and tissue properties following subepithelial cordectomy with complete excision of SLLP, a layer of surface scar was modeled with one column, with an increased lower bound for μ_1 compared to normal SLLP (Table I). This model will be referred to as SE (subepithelial). Subligamental cordectomy was modeled with the same surface scar as in SE, but with complete removal of the ligament (Fig. 1). This model will be referred to as SL (subligamental). A third model simulated an intermediate scenario with transligamental excision (model TL), in which a residual ligament of one-column deep was present. The parameter μ, the shear modulus of the lamina propria gel component, was the main distinguishing feature between the layers. This parameter changes dramatically with scarred tissue.[32]

Glottal width was kept constant across the four scenarios (normal, SE, TL, SL) by incorporating an inelastic implant laterally to maintain a 15-column FEM (Fig. 1). The inelastic implant was simulated by very large values for elastic moduli and viscosity. For simplicity, the simulations were carried out with symmetry, that is, both vocal folds modeled identically.

Optimized Simulation

The implementation of FEM for voice simulation has been detailed previously[30,33] and is briefly summarized in Appendix A (see online only). Multiobjective optimization was integrated with the voice simulator to allow targeted exploration of acoustic possibilities from each vocal fold model, as detailed in Palaparthi et al.[30] Multiobjective optimization aims to find solutions that simultaneously optimize multiple objective functions. The objective functions in this case were F_0 and SPL. The acoustic requirements (objective functions) were set to mimic a male subject with an F_0 target of 120 Hz and SPL target of 70 dB at 30 cm. To optimize these objective functions, two parameters (decision variables) were allowed to vary: subglottal pressure (P_s) and transverse shear modulus of the surface scar, μ_1. Subglottal pressure was allowed to vary within a physiologic range, whereas μ_1 was varied to reflect variability in scarring. The ranges in which the decision variables were allowed to vary are listed in Table I. Vocal fold length L was set to 1.0 cm, thickness T to 0.5 cm, and depth D to 0.5 cm.

The optimized simulation procedure is detailed in Appendix A (see online only). A total of 4,000 solutions per vocal fold model were produced. Each solution was simulated to produce 400 ms of voice signal (Supp. Fig. S1; Supp. Video S1). The voicing was evaluated for periodicity, and a minimum of six cycles must be present for the voicing to be considered viable. Across the four vocal fold models, on average $50.1 \pm 4.2\%$ of the solutions (out of 4,000 per vocal fold model) met the periodicity criterion and were used for further analysis.

Calculation of F_0-SPL Range

The solutions for each vocal fold model were plotted on an F_0-SPL scatter plot as a voice range profile. The area covered by these solutions was computed as a measure of the acoustic capabilities of the respective vocal fold morphology. The area was calculated using a nonconvex hull estimated using Delaunay triangulation.

Sensitivity Analysis

Parameters controlling the vocal fold medial surface shape were varied to perform a sensitivity analysis. Convergence was

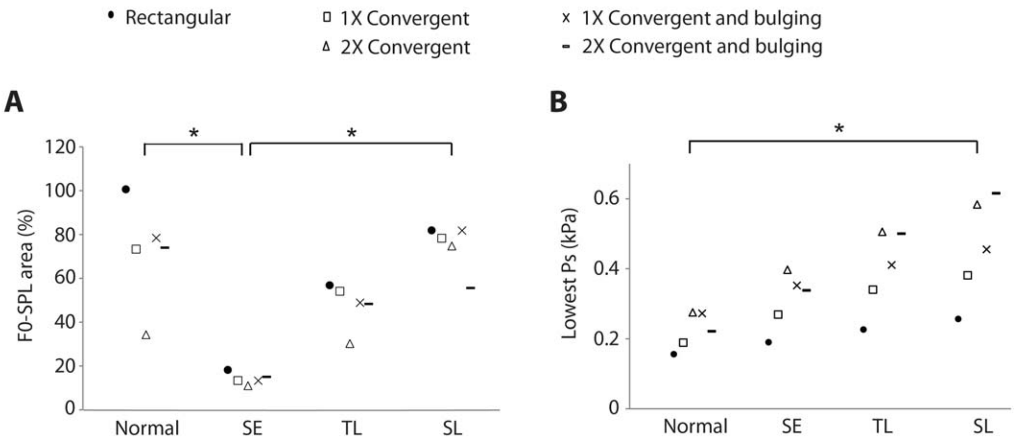

Fig. 3. Effect of resection depth on (A): the distribution of solutions in F_0-SPL space (F_0-SPL area), and (B): the lowest subglottal pressure (Ps). In A, data are plotted as a percentage of the F_0-SPL area occupied by solutions of the normal vocal fold with rectangular geometry. Pairwise comparisons with statistical significance are denoted with asterisks. The other pairwise comparisons did not reach statistical significance. SE = subepithelial cordectomy; SL = subligamental cordectomy; TL = transligamental cordectomy.

defined by lower and upper adduction at the vocal processes (x_{01} and x_{02} in Fig. 1B), and the middle of the surface was allowed to bulge out convexly (x_b in Fig. 1B). Five different shapes were simulated (cases 1–5 in Table I and Fig. 1B).

Statistical Analysis

Statistical calculations were performed with Excel 2010 (Microsoft, Redmond, WA) and SAS 9.3 (SAS Institute Inc., Cary, NC). To determine if the acoustic parameters differed across the four surgical models, one-way analysis of variance (ANOVA) with Tukey's test for pairwise comparison of means was performed, with $\alpha = 0.05$.

RESULTS

Simulation

Supporting Figure S1 shows two example solutions produced by optimized simulation using the normal vocal fold model, highlighting some of the acoustic and aerodynamic features that could be compared between different solutions. Qualitative differences could be appreciated in the time of phonation onset, the time to reach steady state oscillation, and the amplitude of oscillation.

A video demonstrating the simulations is included in Supporting Materials (Supp. Video S1).

Primary Outcome: F_0-SPL Range

The acoustic merit of each vocal fold model was measured by the area in the F_0-SPL plot occupied by the solutions (Fig. 2). A larger area indicates greater pitch range and range of SPL that can be produced by the particular model, given an input range of subglottal pressure P_s and transverse shear modulus of the surface scar, μ_1. Figure 2 shows the distribution of the solutions in F_0-SPL space for the rectangular shaped vocal fold (case 1, Fig. 1B) for each surgical scenario. The F_0-SPL range was the largest for simulations with the normal vocal fold (Fig. 2A). Solutions of subligamental cordectomy covered a range 82% of normal (Fig. 2D), whereas those of subepithelial cordectomy covered a range only 19% of normal (Fig. 2B). Solutions of transligamental cordectomy spread across an intermediate range (57% of normal) (Fig. 2C).

Sensitivity Analysis

The finite element model was defined by a set of geometric parameters, most of which were not targeted for optimization in this study. Before general interpretations can be made about the acoustic consequences of resection depth variation, it is important to examine the sensitivity of the results to the nonvaried parameters. In particular, the prephonatory shape of the medial surface of the vocal folds is known to be an important determinant of phonatory flow and pressure.[34–37] If the results remain qualitatively the same when the medial surface shape is altered, confidence is gained in the relative effects of resection depth and μ of scarred SLLP.

The bulging and convergence parameters that defined the prephonatory vocal fold medial surface shape were varied to produce four different convergent shapes, as shown in Figure 1B. Each was used for optimized simulation as for the rectangular vocal fold above, and the results are shown in Figure 3A. One-way ANOVA comparing the F_0-SPL ranges of the normal vocal fold and the three cordectomy models showed a significant difference, with $F(3,16) = 19.5$, $P < .0001$. A post-hoc Tukey test showed no significant difference between the normal vocal fold and subligamental cordectomy ($P = 0.99$). There was a significant difference between subepithelial cordectomy and normal ($P < .0001$), as well as between subepithelial cordectomy and subligamental cordectomy ($P < .0001$). The relative merits of the SE, TL, and SL models were unchanged by the medial surface shape based on F_0-SPL range. These results support the hypothesis that more extensive ligament resection recovers a larger range of solutions.

Secondary Outcomes

Two vocal input parameters were investigated. There was a statistically significant difference in mean Ps between the four surgical models, as determined by one-way ANOVA ($F(3,16) = 14.2$, $P < .0001$), with the mean Ps progressively higher as the resection depth increased (Supp. Fig. S2A). Tukey post-hoc test showed that the differences were statistically significant between normal vocal fold and transligamental cordectomy ($P = .0013$), normal and subligamental cordectomy ($P = .0001$), and subepithelial and subligamental cordectomies ($P = .0051$). Because the simulation did not explicitly evaluate the phonation threshold pressure, a surrogate measure was obtained by averaging the 10 lowest Ps values which sustained phonation among the solutions for each model (Fig. 3B). There was a statistically significant difference in the lowest Ps between the four surgical models, as determined by one-way ANOVA ($F(3,16) = 4.7$, $P = 0.015$). The only statistically significant difference was between the normal vocal fold and subligamental cordectomy ($P = 0.014$).

Three vocal output parameters were investigated. The F_0 increased with resection depth (Supp. Fig. S2B) (one-way ANOVA $F(3,16) = 61.8$, $P < .0001$, with significant differences between all pairwise comparisons). There was no statistically significant difference in the mean SPL or phonation onset time across the four surgical models (Supp. Fig. S2C–D).

DISCUSSION

The relative acoustic merits of different extents of cordectomies were investigated with computer simulation using a novel optimized simulation strategy. Specifically, the role of the vocal ligament in the setting of mandatory SLLP resection was examined. A tenet in modern vocal fold microsurgery is the maximal preservation of the superficial layer of the lamina propria.[38] This pliable layer facilitates easy conversion of aerodynamic energy into kinetic energy by flow-induced self-sustained oscillations.[34] Minimizing the resection of oncologically uninvolved, deeper tissue (such as the ligament and muscle) should reduce the loss of glottal contact and is generally observed as a principle of vocal fold microsurgery. The simulations here suggest a possible exception to this principle. When cancer resection leaves little to no SLLP, but the ligament can be spared oncologically, it may be advantageous to resect the ligament to enable more favorable voice production. The ligament is much stiffer than the SLLP and helps maintain stability when normal vocal folds are stretched longitudinally to generate higher F_0, with considerably higher subglottal pressure. However, if the mucosa is thinner and less pliable due to scarring, the ligament can hinder tissue oscillation in the F_0 range of the normal speaking voice. Because thyroarytenoid (TA) muscle activation is low in the phonatory position during speech,[39,40] the muscle contributes less longitudinal stiffness than the ligament. Therefore, complete resection of the ligament could be a better option to maintain an adequate speaking voice.

An important caveat to this interpretation is that this study deliberately did not address the glottal gap due to variable healing and filling-in of the surgical defect. We chose to focus on the tissue properties as the variables in this investigation. Our findings were predicated on maintaining a constant glottal width across the different surgical scenarios in the simulations in order to exclude the effect of glottal width. In reality, the reduction of vocal fold depth in the transverse plane after subligamental cordectomy results in a glottal gap or loss of vertical contact. Although this could be partly compensated by hypertrophy or herniation of the TA muscle,[16] granulation tissue formation with collagen deposition, or medialization laryngoplasty,[17,41] the end result is likely more variable. The extent of ligament resection inferiorly along the conus elasticus also differs among surgeons, adding to less predictable vocal outcomes in the clinical setting after subligamental cordectomy. The effect of variable glottal gap size can be studied in future investigations using the same optimized simulation approach, for example, by assigning more layers of the finite element model to muscle in order to simulate muscle expansion following subligamental cordectomy.

A substantially reduced F_0-SPL range after subepithelial cordectomy means that, with the same range of driving subglottal pressures, the dynamic range of pitch and loudness is reduced. One consequence is decreased inflection in speech. Another consequence is that the speaker may have to adapt to altered vocal fold posturing in order to phonate in the more restricted range; that is, it requires motor learning (including somatosensory control) of the new settings. Vocal fold posturing entails control of adduction/abduction, vocal fold length, and muscle activation. For each patient, as the attainable F_0-SPL range narrows, there may be a point beyond which it becomes quite challenging to produce just the right vocal fold posture to speak. The optimized simulations suggest a tradeoff between greater coordination of vocal fold posturing versus higher subglottal pressure. We suspect for most patients it is easier to generate slightly higher subglottal pressure (as after subligamental cordectomy) than to change their habitual vocal fold posturing to target a much smaller target F_0-SPL range (as after subepithelial cordectomy). The increase in subglottal pressure required appears relatively small (0.2 kPa greater for subligamental cordectomy than for subepithelial cordectomy); therefore, it incurs only a minor cost.

The F_0 was noted to increase with progressive resection of the ligament in these simulations. Elevated F_0 is a common finding after cordectomy and is typically attributed to the reduction in vibratory mass due to cancer resection.[9,13,42] However, unlike a simple mass coupled to a spring, the vocal fold consists of several layers of tissue such that a simple relationship between mass and F_0 does not exist.[43] A major reason for the increase in F_0 following cordectomy is likely to be scar formation and scar constituting a significant part of the new vibratory tissue, which increases the stiffness of the vibratory vocal fold. It is the increase in stiffness, not the decrease in mass, that raises F_0.[43] The relatively thin muscle layer in our FEM likely exaggerated the magnitude of F_0 increase as a function of resection depth. A thicker layer of muscle (at the cost of increased computation time for the higher number of FEM columns) would shield the material properties of the lateral implant, which increased the effective stiffness of the vocal fold in the SE, TL, and SL models as the vocal fold depth progressively decreased.

At first glance, the sacrifice of vocal ligament for vocal gain may seem counterintuitive because the ligament plays a unique role in human vocalization by regulating the passive stress in the vocal fold and allowing the SLLP to remain pliable at high frequencies.[44] Loss of the ligament reduces the capability of phonation at high frequencies, for example, singing. However, the necessary SLLP sacrifice will already lead to a significant reduction in F_0 dynamical range. The additional loss of ligament is unlikely to impose additional morbidity in the normal speaking F_0 range. What is gained is a broader F_0-SPL range for the speaking voice.

Although this study was motivated by the reported difference in clinical vocal outcome between subepithelial and subligamental cordectomies,[16] at least one study reported no such difference. Ledda et al.[9] found that the jitter, shimmer, and harmonic-to-noise ratio of voices after either subepithelial cordectomy or subligamental cordectomy were not statistically different from those of nonoperated vocally healthy controls. In contrast, Hillel et al.[16] found differences in voice-related quality of life scores, auditory perceptual ratings, and stroboscopic parameters between the two types of cordectomies. The two studies are not necessarily at odds because they assessed different dimensions of voice, which may explain the divergent interpretations. Furthermore, no direct comparison was made between subepithelial and subligamental cordectomy in Ledda et al.[9] More clinical data comparing the vocal outcomes of the two types of cordectomies are clearly needed to verify the merits of ligament resection.

We wish to emphasize that this study is not a simple endorsement of subligamental cordectomy for all early vocal fold cancers for which subepithelial cordectomy is adequate. According to the European Laryngological Society cordectomy classification system,[45] a subepithelial cordectomy passes through the superficial layer of the lamina propria. This would include a *superficial* subepithelial cordectomy in which most of the SLLP is preserved or a *deep* subepithelial cordectomy in which most or all of the SLLP is removed. The type of subepithelial cordectomy relevant to the study question is the deep version, in which most of the SLLP requires sacrifice. A superficial epithelial lesion that could be removed via a superficial subepithelial cordectomy would not justify a subligamental cordectomy because the voice outcome of a superficial subepithelial cordectomy should be close to normal.

CONCLUSION

Computer simulation utilizing a novel optimized simulation strategy shows greater F_0-SPL range for subligamental cordectomy than subepithelial cordectomy with complete or near-complete resection of SLLP. These results provide theoretical support for the resection of the vocal ligament in cases when most of the SLLP requires sacrifice but the ligament could be spared on oncological grounds. More clinical data comparing the voice outcomes following subepithelial and subligamental cordectomies are needed to corroborate these simulation results to guide surgical intervention.

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