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Voice Outcomes Following Laser Cordectomy for Early Glottic Cancer: A Physical Model Investigation

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Objectives/Hypothesis: The voice effects following laser cordectomy for early glottic cancer are poorly described. We investigated the voice outcomes of subligamentous cordectomy of progressive anterior–posterior extent of excision.

Study Design: Physical phonatory modeling.

Methods: The influence of vocal fold surgical defects and corresponding scar was experimentally investigated using a self-oscillating physical model of the vocal folds and compared with the baseline model without defects or scar.

Results: Results showed that increasing anterior–posterior extent of resection increased phonation threshold pressure and flow rate and reduced excitation of high-order harmonics, resulting in a more breathy and rough voice production. However, it was found that voice production was improved with the placement of scar, which increased both excitation of high-order harmonics and the harmonic-to-noise ratio.

Conclusions: Although large anterior–posterior surgical resections resulted in progressive impact on vocal measures, a limited excision of the vocal fold cover surprisingly demonstrated minimal voice changes. Further investigations are required to define the acceptable extent of surgical resection that may result in optimal voice outcomes.

Key Words: Cancer, larynx, vocal cord, voice, laser, glottic.

Level of Evidence: N/A

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INTRODUCTION

Published evidence has demonstrated comparatively similar voice outcomes when early vocal fold cancer is treated by either primary radiation therapy or transoral laser microsurgical excision, or laser cordectomy.[1,2] As such, patients who undergo surgical resection are able to avoid the substantial toxicity of external beam radiation therapy while achieving equivalent long-term voice outcomes. Surgical patients can also enjoy a single treatment and avoid the 6-week treatment duration of radiation therapy. With early stage neoplastic lesions of the vocal fold (carcinoma in situ or T1a carcinomas), tumors can be definitively treated through an outpatient procedure. As such, further characterization of the vocal effects following surgery should be investigated.

To date, the vast majority of the literature has concentrated on voice outcomes from laser cordectomy when compared with radiotherapy. Few reports have investigated the voice outcomes of early stage as compared with advanced stage cordectomies,[3] defined by the European Laryngological Society (ELS) classification.[4] Yet there has been little guidance to achieve optimal voice outcomes within early stage laser cordectomies. This leaves little data-driven guidance to the laryngological surgeon as to the optimal extent of cordectomy for early glottic carcinoma, apart from anecdotal and theoretical descriptions of vocal fold physiology. To the best of our knowledge, one study to date has investigated the voice outcomes as it relates to the extent of cordectomy in early glottic cancer.[5]

Traditionally, laryngological surgery has been guided by Hirano's emphasis on the importance of the vocal fold cover layer.[6] The specialized layers of the vocal fold's lamina propria are impossible to replace, and the surgeon must preserve as much of the natural fold as possible to reduce scarring and improved vibratory motion. As such, the traditional teaching for laser cordectomy recommends excision of only what is absolutely required from an oncologic standpoint. The ELS classification scheme defines laser cordectomies by their depth (i.e., medial–lateral extent); little emphasis is given to the extent of resection in the anterior–posterior (A-P) direction. The aim of the present study is to understand the effect of increasing A-P resection of a type II ELS (subligamentous) laser cordectomy. To achieve this aim, we utilized a self-oscillating physical model that has been previously established.[7]

MATERIALS AND METHODS

The experimental setup is similar to that used in previous studies.[7–10] More details of the setup can be found in these

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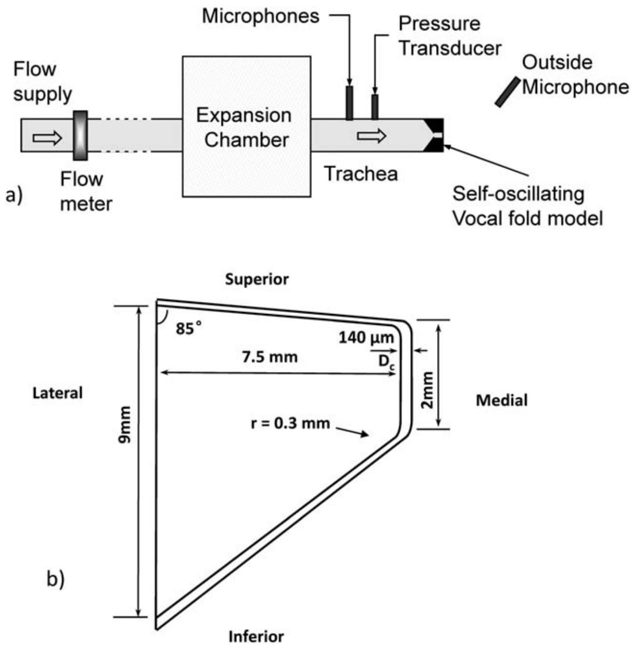

Fig. 1. Sketch of (a) the experimental setup and (b) the coronal cross-sectional geometry of the two-layer physical model.

previous studies. As shown in Figure 1a, the setup consisted of an expansion chamber (with a rectangular cross section of the dimensions 23.5 × 25.4 cm and 50.8 cm long) simulating the lungs, an 11-cm-long straight circular polyvinyl chloride tube (inner diameter of 2.54 cm) simulating the tracheal tube, and a self-oscillating model of the vocal folds. The expansion chamber was connected upstream to a pressurized airflow supply through a 15.2-m-long rubber hose. No vocal tract was used in this study to avoid possible source–tract interaction.

The physical models used in this study had a uniform cross-sectional geometry along the A-P direction. The cross-sectional geometry was defined in the same way as that used in prior studies.[9,11] For the data presented in the following text, all vocal fold models had identical geometry, with a medial surface thickness (dimension in the flow direction) of 2 mm and a lateral surface thickness of 9 mm (see Fig. 1b). The A-P dimension of the vocal folds was 17 mm. The vocal fold models were made by mixing a two-component liquid polymer solution (Ecoflex0030; Smooth On, Easton, PA) with a silicone thinner solution, with different composition ratios resulting in different model stiffness. For this study, the vocal fold model had a Young's modulus of about 2.5 kPa. To simulate the effect of the epithelium layer, an additional layer of the silicone compound solution, with a Young's modulus of about 66 kPa and a thickness about 140 μm, was added to the outer surface of the one-layer vocal fold. For the baseline phonatory condition, two identical vocal fold models were placed in opposition for phonation. Two progressive variations were used to create the cordectomy model. Individual vocal folds models with defects of 5 mm and 10 mm were fashioned. A surgical scalpel was used to excise the pliable vocal fold cover layer at a measured depth of 1 mm. The defects were centered on A-P midpoint. Following the phonation of the 5-mm and 10-mm cordectomy models, the defects were then filled with glue to model postsurgical vocal fold scar formation. Each cordectomy model was phonated opposite an unaltered vocal fold.

For each physical model configuration, the flow rate was increased in discrete increments from zero to a value above onset. At each step, after a delay of about 1 to 2 seconds after the flow rate change, the mean subglottal pressure (measured at 2 cm from the entrance of the glottis), mean flow rate, acoustic pressure inside the tracheal tube (2 cm from the entrance of the glottis), and outside acoustic pressure (about 20 cm downstream and about 30° off axis) were measured for a 1-second period. These data were recorded at a sampling rate of 50 kHz.

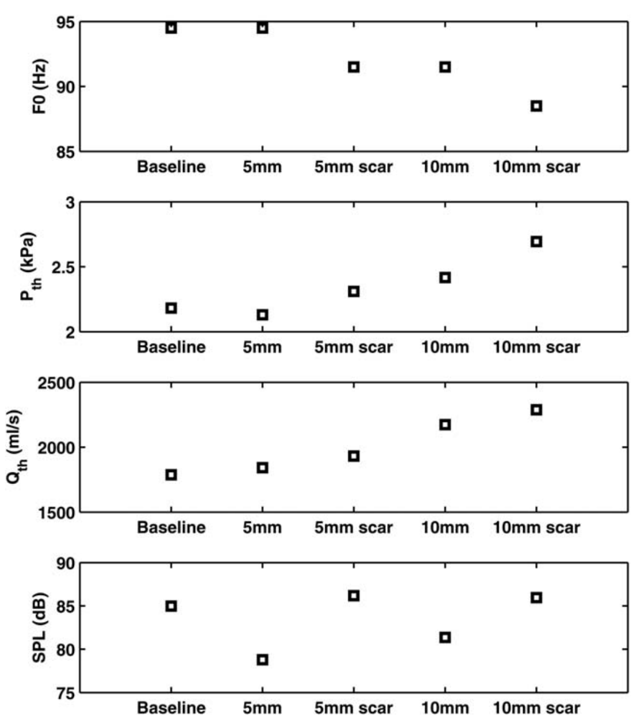

Fig. 2. The onset phonatory frequency (F_0), phonation threshold pressure (P_{th}), threshold flow rate(Q_{th}), and outside sound pressure level (SPL) are displayed as functions of the extent of cordectomy in the physical model.

RESULTS

As shown in Figure 2, phonation threshold pressure (P_{th}), threshold flow rate (Q_{th}), and onset fundamental frequency (F_0), were not grossly affected by the 5-mm cordectomy defect. The more extensive 10-mm cordectomy defect led to a slight decrease in F_0. The decrease

TABLE I.
Onset Fundamental Frequency, Phonation Threshold Pressure, Sound Pressure Level, and Threshold Flow Rate as Functions of the Extent of Cordectomy.

Extent of Excision	Onset Fundamental Frequency, Hz	Phonation Threshold Pressure, kPa	Sound Pressure Level, Pa	Threshold Flow Rate, m/s
Baseline	94.5	2.182	0.355	1,787
5-mm cordectomy	94.5	2.13	0.174	1,843
5-mm cordectomy with scar	91.5	2.31	0.407	1,932
10-mm cordectomy	91.5	2.417	0.234	2,174
10-mm cordectomy with scar	88.5	2.694	0.397	2,288

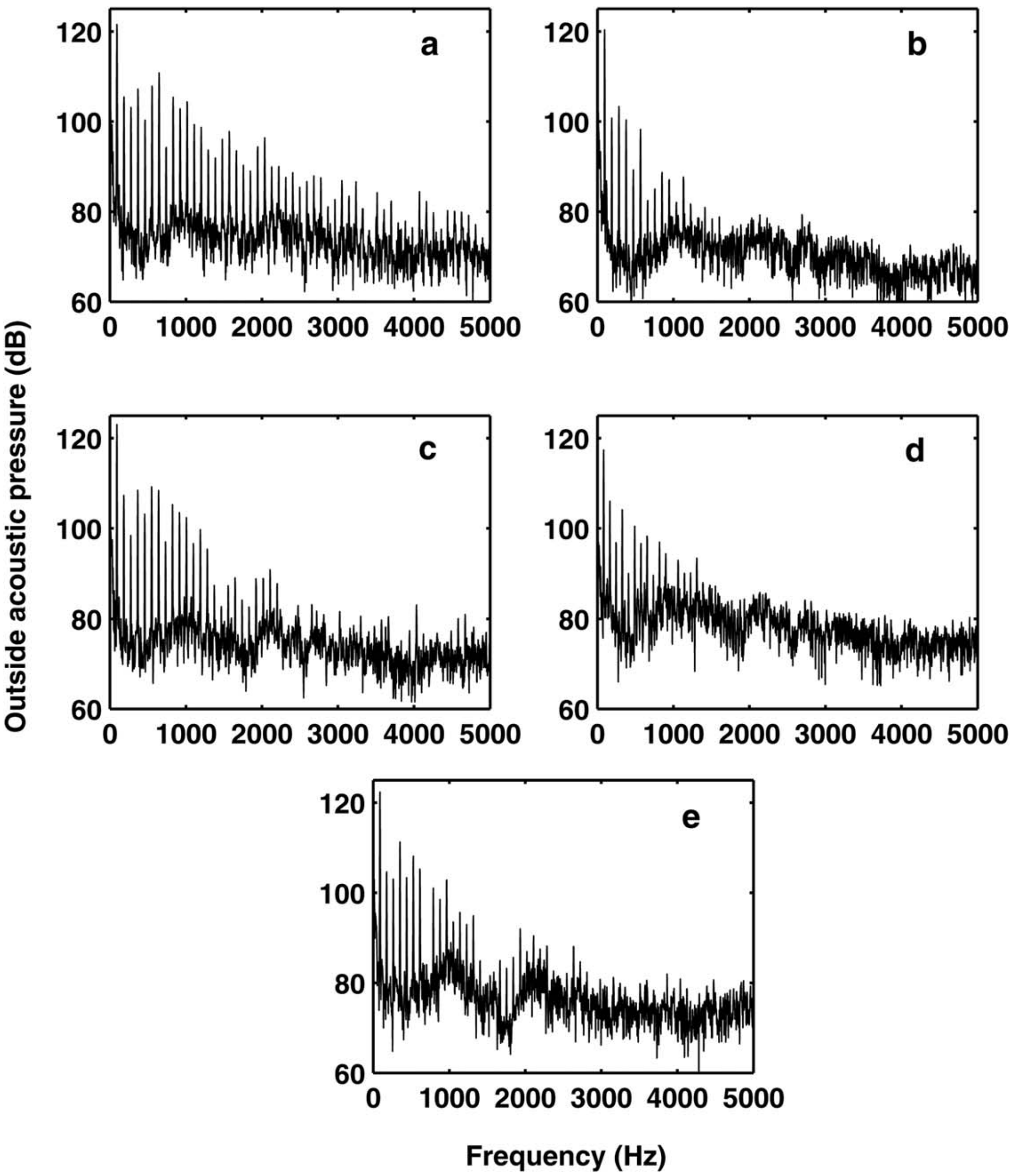

Fig. 3. The outside sound spectra at a subglottal pressure of 10% above the corresponding phonation threshold pressure are displayed by progressive extent of cordectomy: (a) baseline, (b) 5-mm cordectomy, (c) 5-mm cordectomy with scar, (d) 10-mm cordectomy, and (e) 10-mm cordectomy with scar.

in F_0 was probably due to the partial removal of the stiffer epithelium layer, which reduced the overall stiffness. Although reduction in vocal fold stiffness often leads to reduced phonation threshold pressure, Figure 2 shows that the phonation threshold pressure increased with increasing extent of excision, indicating the excision may have reduced the fluid–structure interaction between the two folds and the glottal airflow. Increased A-P extent of excision also led to monotonic increase in phonation threshold flow rate. High-speed images of vocal fold vibration also showed that whereas complete glottal closure during vibration was observed in the baseline model, it was not observed in models of 10-mm excision. The phonation threshold pressure and flow rate were further increased with the placement of scar, whereas the onset frequency was lowered even more with the placement of scar (Table I).

In contrast to the relatively small changes in F_0, P_{th}, and Q_{th}, Figure 3 shows that the 5-mm excision significantly reduced the outside sound pressure level. The 10-mm excision case led to similar reduction in the outside sound pressure. Although we expected placement of scar would further disrupt vocal fold entrainment and may affect voice production, Figure 3 shows that addition of

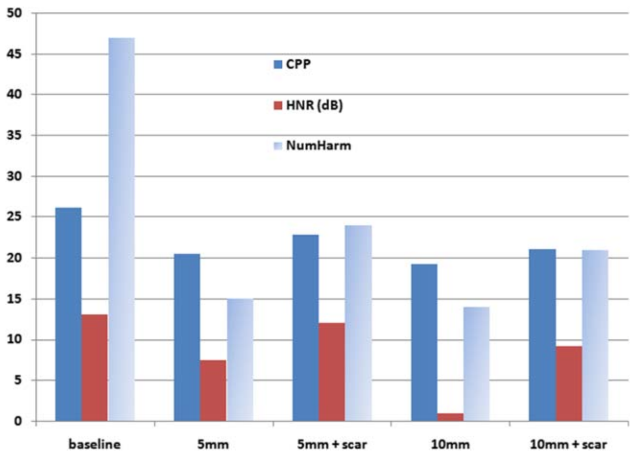

Fig. 4. Changes in voice spectra are displayed by extent of cordectomy as quantified by the cepstral peak prominence (CPP), the harmonic-to-noise ratio (HNR), and the number of harmonics below 5 kHz that are visible above the noise baseline (NumHarm). [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

the glue (scar) actually restored the outside sound pressure level back to that in the baseline condition.

Figure 3 shows the outside sound spectra at a subglottal pressure of 10% above the corresponding phonation threshold pressure. The changes in voice spectra were further quantified by the cepstral peak prominence (CPP), the harmonic-to-noise ratio (HNR), and the number of harmonics below 5 kHz that are visible above the noise baseline (NumHarm),[12] and are shown in Figure 4.

Increasing A-P extent of excision significantly reduced excitation of high-order harmonics but increased noise production at high frequencies. This led to monotonic decrease in CPP, HNR, and NumHarm with increasing A-P extent of excision, with the produced sound becoming increasing breathy and rough. The placement of the surgical scar, or glue, however, led to partial restoration of the voice quality, with all three measures improved as compared with the corresponding case without scar.

It is noted that the outside sounds produced at onset and 5% above onset were also analyzed and the same acoustic effects (sound pressure level, high-order harmonics excitation) of the excision and the scar were observed.

The above experiments were repeated with another vocal fold model with a body-cover structure. Similar results regarding the detrimental effects of the defect and voice restoration effects of the scar were observed. One advantage of the physical models is the reliable good control of vocal fold geometry and stiffness, and experimental results are highly repeatable, as demonstrated in this study as well as previous investigations.[9–12]

DISCUSSION

Our study aimed to characterize the effects of voice following progressive A-P resection of the vocal fold cover layer. The findings herein demonstrate a progressive decline in voice outcomes as larger defects were created in the vocal cover, consistent with previous understanding based on the body-cover theory of Hirano.[6] However, the effect of the minimal resection of 5 mm (or about one-third of the A-P dimension of the 17-mm vocal fold) demonstrated little change of voice measures. The results also showed that voice production was partially restored with the placement of the scar, which led to increased high-order harmonics excitation and sound pressure level when compared to the corresponding cases without scar. This may be surprising, considering that vocal fold scarring is often considered detrimental to voice quality. Although the specific mechanisms underlying the observed improvement are unclear, it is likely that the addition of the scar may improve the entrainment of the two folds by the glottal airflow compared to vocal folds with a unilateral dent in the middle portion of the cover layer. Further theoretical analysis of the location of vocal fold scars on vocal fold entrainment and the resulting vibration pattern is required.

The effects of increased cover layer excision on voice outcomes were also investigated in a clinical study by Hillel and colleagues.[5] In their study, which included perceptual and patient-centered measures, the patients who underwent a more extensive ELS type II cordectomy trended toward improved voice outcomes as compared with the more limited ELS type I (subepithelial) cordectomy. The findings of Hillel et al., although limited by sample size, suggested that patients might benefit by increasing the depth of cover layer excision. Direct comparison between Hillel's study and the present study are challenging, due to the difference in measures of resection (medial–lateral vs. A-P). However, both studies do point out possible exceptions to the traditional vocal fold surgical teaching. In the present study, a resection of 5 mm (or approximately one-third of the A-P dimension) results in very minor injury to the voice, especially when filled with scar. In the study by Hillel et al., a deeper medial extent to the surgical resection may lead to improved voice outcomes. Although it is unclear what mechanisms are underlying the observed improvement in voice outcome, both studies seem to point to the need for further systematic investigation of the effects of the extent of surgical resection.

The present study has many shortcomings, the most prominent involving the inherent simplifications of the physical model. Although the present study's self-oscillating vocal fold physical model has been utilized in many previous studies to understand phonation mechanisms, it is still a simplification of the inherently complex vocal fold physiology. Additionally, the physical vocal fold cannot model the complex healing process of the vocal fold cover. Although vocal scar states were included in the present study, the process of vocal fold scar is a variable and poorly understood entity. Further experiments using physiologically more realistic models of phonation are required to verify the results of this study.

CONCLUSION

The A-P extent during laser surgery for early glottic cancer was investigated with the use of a self-oscillating physical model. Phonatory variables, including phonation onset threshold pressure and phonatory harmonics, as well as acoustic measures based on the outside sound spectra, were diminished with increasing resections of the vocal fold cover. Surprisingly, the incorporation of vocal fold scar within the surgical defect improved the phonatory measures as compared with the corresponding defect size. Initial data suggest that small A-P excisions may result in negligible voice effects, although further investigations are required.

BIBLIOGRAPHY

1. Goor KM, Peeters AJ, Mahieu HF, et al. Cordectomy by CO2 laser or radiotherapy for small T1a glottic carcinomas: costs, local control, survival, quality of life, and voice quality. *Head Neck* 2007;29:128–136.
2. van Gogh CD, Verdonck-de Leeuw IM, Wedler-Peeters J, Langendijk JA, Mahieu HF. Prospective evaluation of voice outcome during the first two years in male patients treated by radiotherapy or laser surgery for T1a glottic carcinoma. *Eur Arch Otorhinolaryngol* 2012;269:1647–1652.
3. Vilaseca I, Huerta P, Blanch JL, Fernandez-Planas AM, Jimenez C, Bernal-Sprekelsen M. Voice quality after CO2 laser cordectomy—what can we really expect? *Head Neck* 2008;30:43–49.
4. Remacle M, Eckel HE, Antonelli A, et al. Endoscopic cordectomy. A proposal for a classification by the Working Committee, European Laryngological Society. *Eur Arch Otorhinolaryngol* 2000;257:227–231.
5. Hillel AT, Johns MM III, Hapner ER, Shah M, Wise JC, Klein AM. Voice outcomes from subligamentous cordectomy for early glottic cancer. *Ann Otol Rhinol Laryngol* 2013;122:190–196.
6. Hirano M, Kakita Y. Cover-body theory of vocal fold vibration. In Daniloff RG, ed. Speech Science: Recent Advances. San Diego, CA: College-Hill Press; 1985:1–46.
7. Xuan Y, Zhang Z. Influence of embedded fibers and an epithelium layer on glottal closure pattern in a physical vocal fold model. *J Speech Lang Hear Res.* In press.
8. Zhang Z, Neubauer J, Berry DA. The influence of subglottal acoustics on laboratory models of phonation. *J Acoust Soc Am* 2006;120:1558–1569.
9. Zhang Z. Dependence of phonation threshold pressure and frequency on vocal fold geometry and biomechanics. *J Acoust Soc Am* 2010;127:2554–2562.
10. Mendelsohn AH, Zhang Z. Phonation threshold pressure and onset frequency in a two-layer physical model of the vocal folds. *J Acoust Soc Am* 2011;130:2961–2968.
11. Zhang Z. Characteristics of phonation onset in a two-layer vocal fold model. *Acoust Soc Am* 2009;125:1091–1102.
12. Zhang Z, Kreiman J, Gerratt B, Garellek M. Acoustic and perceptual effects of changes in body layer stiffness in symmetric and asymmetric vocal fold models. *J Acoust Soc Am* 2013;133:453–462.