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What is This?
Voice Outcome of Modified Frontolateral Partial Laryngectomy in Excised Canine Larynges and Finite Element Model

Hongming Xu, MD1, Anton A. Kvit2, Erin E. Devine2, Xinjiang Ying, MD, PhD1, and Pin Dong, MD, PhD1

Abstract

Objective. To evaluate vocal parameters after modified frontolateral partial laryngectomy (MFLPL) and frontolateral partial laryngectomy (FLPL) in both excised canine and finite element models.

Study Design. FLPL and MFLPL were compared, using a prospective paired case control laboratory study with excised canine larynx and computational modeling.

Setting. Basic science study conducted in university laboratory.

Methods. FLPL and MFLPL were performed serially on 9 excised canine larynges. The excised larynx bench apparatus was used to collect phonation threshold pressure (PTP) and high-speed video data. A finite element model was built to compare a normal vocal fold with applied tension, a cut fold with no applied tension (simulating FLPL), and a cut fold with applied tension (simulating MFLPL). Stress values and distributions across the 3 conditions were computed.

Results. The mean PTP increase after MFLPL (15.45-17.46 cmH2O) was not statistically significant. In the excised canine model, fundamental frequency (F0) showed a significant increase for the MFLPL (P = .039). Differences in vibration amplitudes were not statistically significant. Von Mises stress distribution was most similar between the MFLPL model and the normal fold. Maximum von Mises stresses at the midline were 17.56, 21.63, and 5.10 kPa for the normal, MFLPL, and FLPL, respectively, and 47.57, 63.98, and 101.97 kPa at the peripheries.

Conclusions. From these results, we conclude that MFLPL has the potential to give a better voice outcome while avoiding tracheotomy in partial laryngectomy patients. In vivo study in canines to examine the healing process would lend further evidence-based support for this surgical method.

Keywords

partial laryngectomy, frontolateral partial laryngectomy (FLPL), modified frontolateral partial laryngectomy (MFLPL), excised canine larynx, finite element analysis

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Introduction

Treatment for early-stage (T1, T2) glottic carcinomas is debated and varies from center to center. Frontolateral partial laryngectomy (FLPL), radiation therapy, or endoscopic laser excision are used successfully for the treatment of T1 and T2 glottic carcinomas with similar oncologic and functional outcomes.1 Although an increasing number of patients have been treated with transoral laser excision in the past decade, partial laryngectomy is still offered to patients with more advanced tumors and patients in whom the anterior commissure is involved. In cases of anterior commissure involvement, local control rates with transoral laser excision are quite high, but survival rate is lower than in open partial laryngectomy.2 However, voice outcome is greatly influenced by resection of the anterior commissure during surgery.

Quality of life after partial laryngectomy strongly depends on vocal function and airway adequacy. We therefore developed a novel approach: modified frontolateral partial laryngectomy (MFLPL) without tracheotomy.3 In this procedure, the inner side of the sternohyoid muscle is drawn into the laryngeal lumen and sutured to the incisal margin of the unaffected side after frontolateral partial laryngectomy, as well as to the false vocal fold ipsilateral to the lesion. The contralateral fascial flap of the sternohyoid muscle is turned over and sutured to the ipsilateral side, closing the laryngeal luminal defect by the muscular fasciae and creating a “ladder” shape with an enlarged intraluminal diameter (Figure 1). From clinical practice and animal

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experimentation, this approach is indicated to be a safe and reliable method for excising the anterior 20% of the vocal fold and thyroid cartilage without the necessity of tracheotomy.3,4 The voice outcome of this novel approach is suggested to be more satisfactory by our clinical practice, due to maintenance of proper tension in the remaining vocal fold using the sternohyoid myofascial flap. The function of the anterior commissure is simulated by drawing the inner side of the sternohyoid muscle into the laryngeal lumen and suturing it to the anterior incisal margin.3

Finite element analysis has been used extensively in vocal fold modeling to approximate measurements that are difficult to obtain experimentally, such as stress distributions.5-7 Parameters derived from finite element models, such as stress magnitude and distribution, could predict areas of potential tissue damage and confirm physiologically observed vibration trends.8,9 This can help discern between surgical procedures to determine a more favorable approach.10

We hypothesized that tension of the remaining vocal fold is important for the voice outcome after partial laryngectomy.11,12 In this study, MFLPL and FLPL were simulated in an excised larynx model to investigate whether MFLPL can achieve better voice outcome over the traditional surgical approach using high-speed digital imaging and aerodynamic analysis. Finite element models of normal, FLPL, and MFLPL vocal fold surgeries were built to quantify the amplitude and stress distribution under each condition to further study differences between the procedures.

Materials and Methods

Larynges

Nine larynges were excised postmortem from canines sacrificed for non–research purposes, and therefore the research was exempt from animal care and use review. After excision, the larynges were examined for evidence of trauma or disorders and frozen in 0.9% saline solution.

Surgical Technique

The first surgical technique was simulative FLPL. A perichondrial flap was elevated off the bilateral thyroid lamina before the thyroid lamina was incised. The thyroid lamina was incised vertically along both sides, 4 to 5 mm (20% of larynx) from the anterior commissure. The right laryngeal mucosa and soft tissue were dissected from the thyroid lamina, achieving separation from the anterior commissure to the arytenoid cartilage. Excision extended inferiorly from the right inferior border of the false vocal fold to the lower border of the true vocal fold. The posterior edge included the vocal process of the right arytenoid cartilage, whereas the contralateral edge was at the same level as the left thyroid lamina margin vertically. Reconstruction of the cordectomy defect was accomplished by mobilizing the false fold mucosa and suturing over the cordectomy defect. Reconstruction of the anterior larynx was achieved by reapproximation of the left vocal ligament and incisal margin of right false fold anteriorly, and reapproximation of the thyroid cartilages to one another (Figure 2).

The second surgical technique used was simulative MFLPL. This procedure was conducted in the same excised larynx, following FLPL and initial functional analysis. The main difference between MFLPL and FLPL was the repair method. False fold mucosa was also used to reconstruct the cordectomy defect. The inner side of the perichondrial flap prepared in advance was drawn into the laryngeal lumen so the perichondrial flap could be sutured to the incisal margin of the left vocal fold and the right false fold. This flap replaced the function of sternohyoid muscle. The anterior defect was sealed by silica gel (Figure 2).

Apparatus

The superior cornu and posteriorsuperior part of the thyroid cartilage were dissected away bilaterally to facilitate insertion of lateral micrometers into the arytenoid cartilage. The larynx was mounted on the apparatus as specified by Jiang and Titze.13 The trachea was fastened to a pipe connected to...
the pseudolung, which served as a constant pressure source. Stabilization of the larynx was accomplished with 2 lateral 3-pronged micrometers inserted into each arytenoid cartilage.

The pseudolung used to initiate and sustain phonation simulated the human respiratory system. Pressurized airflow passed through 2 Concha Therm III humidifiers (Fisher & Paykel Healthcare Inc, Laguna Hills, California) in series to humidify and warm the air. Throughout the experiment, 0.9% saline was applied to the vocal folds to maintain hydration. Airflow was controlled manually and measured by an Omega airflow meter (model FMA-1601A, Omega Engineering Inc, Stamford, Connecticut). Pressure measurements were taken immediately before the air passed into the larynx using a Heise digital pressure meter (901 series, Ashcroft Inc, Stratford, Connecticut).

Experimental Methods

Original FLPL and MFLPL geometry measurements were taken before each procedure using a digital caliper. After mounting the larynges, airflow was gradually increased until onset phonation threshold pressure (PTP) was reached, at which time pressure was recorded. A high-speed digital camera (Fastcam-ultima APX; Photron USA, Inc, San Diego, California) recorded vocal fold vibration with a subglottal pressure of PTP. The resolution was 2563 × 512 pixels, with a recording rate of 4000 frames per second. After phonation onset, 6 videos were recorded. After data collection for the FLPL procedure was completed, the larynx was removed from the apparatus. MFLPL was carried out on the same excised larynx using the perichondrial flap to reconstruct the frontolateral part of the larynx. The larynx was remounted on the apparatus and aerodynamic and high-speed video data were collected.

Data Analysis

The pressure at initiation of phonation was recorded as the onset phonation threshold pressure. PTP was determined during each trial from a real-time graphic display generated by a customized LabVIEW 8.5 program.

A customized MATLAB program (version 7.2.0.232 [R2006a]; The MathWorks, Inc, Natick, Massachusetts) was used to analyze high-speed data via digital kymography (DKG), a line-scan imaging technique. The vibratory properties of the upper and lower left vocal fold lips and right false vocal fold were quantified via DKG. Threshold-based edge detection, manual wave segment extraction, and nonlinear least squares curve fitting using the Fourier Series equation were used to determine the most closely fitting sinusoidal curve. Coefficients of the wave function were used to derive the amplitude, frequency, and phase shift of the right false fold and the upper and lower left vocal fold lips.

Statistical Analysis

Paired t tests were performed to compare differences in frequency and amplitude between FLPL and MFLPL. If data did not have a normal distribution, Wilcoxon signed rank tests were performed. A significance level of α = .05 was used.

Finite Element Model

COMSOL Multiphysics (Version 4.3a, 2013) was used to build linearly elastic finite element models of a normal vocal fold, as well as FLPL and MFLPL surgeries. Models were defined in Cartesian coordinates, with the x-, y-, and z-dimensions corresponding to the medial-lateral, inferior-superior, and anterior-posterior directions, respectively. The geometry (Figure 3) was determined by averaging measurements taken from the excised vocal folds used in this study. For all 3 models, the height (y-direction) was 7 mm for the lateral edge and 2.5 mm for the medial edge and the thickness (x-direction) was 3 mm. The anterior-posterior length was measured in the FLPL and MFLPL conditions and the average of glottal length was used in the model (9.35 mm and 10.18 mm). The normal model glottal length was calculated as 20% greater than the average measurement results of the FLPL condition (9.35 + 9.35 × 20% = 11.22 mm) in the normal vocal fold. All models included a 1 mm14 cover over the body. Material properties were based on previously published measurements and models and can be seen in Table 1.15-21 All of the models were meshed.
using 5850 3-D prism shaped elements and were solved for 82,348 degrees of freedom.

In the FLPL model, the anterior, posterior, and lateral faces of the vocal fold were constrained. In the MFLPL and normal models, the posterior face was constrained, while the anterior and lateral faces were stretched prior to vibration and constrained at that distance afterwards. The stretch lengths were chosen based on the average stretch of the excised models, 0.83 mm for MFLPL and 0.8 mm for normal (the actual measurement result of FLPL was 9.35 mm). Vibration was modeled in 2 steps, a stationary analysis that stretched the vocal fold, followed by a frequency domain analysis that vibrated the vocal fold at 150 Hz, within the range observed in the excised folds. Application of boundary loads on the subglottal and intraglottal faces at a 90-degree phase difference induced oscillation, as in Gunter.6 The loads varied sinusoidally, with the subglottal pressure ranged from 500 Pa to 1500 Pa, while the intraglottal pressure ranged from −250 Pa to 750 Pa, within reported physiological pressure ranges22,23 and ranges used in previous models.5,18

Vibration amplitudes for the normal, FLPL, and MFLPL vocal folds were recorded at the anterior-posterior midline of the intraglottal surface, 2.5 mm below the superior surface (Figure 3). The z-direction normal stress due to elongation alone was averaged from the entire geometry in the normal and MFLPL models. Von Mises stress distribution in 3 dimensions, which indicates damage-inducing stress threshold in elastic tissues,6,10 was also recorded.

**Results**

The phonation threshold pressure is the lowest subglottal pressure needed to sustain vocal fold oscillation.24 Clinically, it is considered a measure of ease of phonation.25 Since the anterior part of the larynx was separated in MFLPL, which increased the area of the glottis, PTP after MFLPL was predicted to increase compared to PTP in the conventional operation. PTP was found to increase from 15.45 ± 2.94 cmH2O after FLPL to 17.46 ± 5.30 cmH2O after MFLPL (Table 2), but this difference was not statistically significant (P = .359, Wilcoxon signed rank test), indicating the ease of phonation level was not severely impacted by the new approach.

The fundamental frequency is an important index of laryngeal function. Analysis of high-speed imaging data showed the F0 of both upper and lower lips of the left vocal fold to be significantly different (P = .039) between MFLPL and FLPL. A significant difference (P = .004) was also noted in the right false fold F0 by kymographs (Table 2). Although differences in amplitude of the mucosal wave were discernible, they were not statistically significant (Table 2).

The normal vocal fold finite element model produced a vibration amplitude of 0.684 mm, while the FLPL model produced 0.838 mm amplitude, and the MFLPL produced 0.554 mm amplitude.

The average z-direction stress due to elongation alone was 8.86 kPa in the normal model and 11.51 kPa in the MFLPL model and was nonexistent in the FLPL model since it was not elongated.

Von Mises stress distribution in the MFLPL model was more similar the normal fold model than the FLPL model (Figure 4). Maximum von Mises stress at the anterior-posterior midline was 17.56 kPa in the normal model, 21.63 kPa in the MFLPL model, and 5.10 kPa in the FLPL model. Maximum von Mises stress at the anterior and posterior peripheries was 47.57 kPa in the normal fold, 63.98 kPa in the MFLPL, and 101.97 kPa in the FLPL.

**Discussion**

We developed a novel operation, modified frontolateral partial laryngectomy, which was designed to avoid tracheotomy. Based on clinical observation, voice outcomes of patients who received this approach were found to be more satisfactory than conventional FLPL. We believe that tension of the remaining vocal fold achieved with MFLPL yielded these results. The goals of this study were to evaluate whether using a sternohyoid myofascial flap to reconstruct the anterior

![Figure 3](image-url) 3-D finite element vocal fold model composed of 5850 prism shaped elements. Red dot indicates the point where maximum vibration amplitude (x-displacement) was recorded.

**Table 1.** Finite Element Model Material Properties.

<table>
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part of the larynx improves vocal outcome and to assess if vibratory function of the reconstructed glottis is enhanced after the novel surgery compared to the conventional approach. F0 and intensity ranges of phonation are considered primary factors limiting vocal function outcome following hemilaryngectomy, where the anterior commissure and insertion point for the cricothyroid muscle are removed. F0 has been observed to decrease significantly after FLPL. Therefore, the change in F0 after MFLPL was a main focus of our study. Our results showed that the F0 of both the remaining left vocal fold and right false fold were significantly increased after MFLPL compared to FLPL, while the amplitude was not significantly decreased after MFLPL, indicating the enhancement of vibratory function. It is also reported that median F0 of normal canine larynges obtained from high-speed digital imaging was 210 Hz, which is consistent with our MFLPL results.

After reconstruction using the sternohyoid myofascial flap in the MFLPL surgery, the natural triangular contour of the glottis was transformed into a trapezoidal shape. Thus, the glottic area was greater, which impacted airflow mechanics. However, results show that there was no significant difference in PTP between FLPL and MFLPL.

The finite element model results showed that FLPL model had a higher vibration amplitude (.838 mm) than in the normal fold (.684 mm), which was relieved with application of tension in the MFLPL model (.554 mm). Amplitude values were similar to our excised vocal fold observations, as well as results from previous studies. While our model incorporated directly applied loads, which prevented us from analyzing the effect of elongation on frequency, the effect on amplitude corresponded with observations in the excised vocal folds.

The goal the finite element model was to evaluate if tension applied in the MFLPL procedure significantly changed stress distributions, which may indicate secondary trauma of remaining vocal fold. The average stresses in the anterior-posterior z-direction due to elongation were similar in the MFLPL and normal models. Even though the MFLPL resulted in a slightly higher stress (11.51 kPa), it was still far below the reported damage thresholds. Thus, MFLPL creates a more natural stress distribution, which in turn could result in vibration that is closer to an intact vocal fold. This was evident when comparing the maximum von Mises stress distributions between the normal, FLPL, and MFLPL models (Figure 4). The normal and MFLPL models both had a more even stress distribution between the anterior-posterior midline and the peripheries, as well as more evenly inferior-superior distributed stress along the peripheral medial surface. In contrast, the maximum stress difference between the midline and periphery of the FLPL model was significantly higher than the other models. Additionally, stress in the FLPL vocal fold was more concentrated in the superior aspect of the anterior and posterior sides near the medial surface. The maximum stress at the edges of the FLPL model was more than 50 kPa higher than maximum stresses observed in the other 2 models, which could cause tissue remodeling in the FLPL fold, potentially

| Table 2. Mean, Standard Deviation, and P-Values of Excised Larynx Parameters. |
|---------------------------------|------------------------------|----------------|----------------|----------------|
|                                | PTP  | LU-amp | LL-amp | RFF-amp | LU-F0 | LL-F0 | RFF-F0 |
| FLPL                            | 15.45 ± 2.94 | 0.54 ± 0.19 | 0.47 ± 0.20 | 0.20 ± 0.19 | 152.86 ± 45.59 | 152.92 ± 45.75 | 125.17 ± 53.38 |
| MFPL                            | 17.46 ± 5.30 | 0.38 ± 0.24 | 0.35 ± 0.22 | 0.15 ± 0.11 | 221.12 ± 76.44 | 220.61 ± 76.49 | 216.35 ± 70.93 |
| P value                         | .359 | .130 | .274 | .595 | .039 | .039 | .004 |

Abbreviations: PTP, Phonation threshold pressure; LU-amp, left upper amplitude; LL-amp, left lower amplitude; RFF-amp, right false fold amplitude; LU-F0, left upper F0; LL-F0, left lower F0; RFF-F0, right false fold F0.

**Figure 4.** Maximum von Mises stress distribution during 150 Hz vibration in the original, frontolateral partial laryngectomy (FLPL), and modified frontolateral partial laryngectomy (MFLPL) models. A, normal fold model; B, MFLPL model; C, FLPL model.
limiting wound healing and decreasing vocal quality outcome. However, the effects of stress on tissue remodeling and wound healing in the vocal folds require further study. While precise stress values might be slightly obscured by edge effects, the distribution trends clearly showed that the MLFPL procedure results in more natural stress patterns.

The false vocal fold mucosal flap technique is a glottic reconstruction method described to improve vocal function after frontolateral partial laryngectomy. Biacabe et al reported that the FVF mucosal flap was involved in laryngeal closure after FLPL with glottal reconstruction, which can improve vocal results in selected cases of T1a squamous cell carcinoma of the glottis when FLPL is the adequate surgical treatment. The results of this study provide objective support for the use of this flap to reconstruct the glottis. Stable vibration of FVF flap was observed with HSDI after both FLPL and MFLPL, the amplitude of which is half of the left remaining vocal fold. The F0 of right false fold was also significantly improved after MFLPL versus FLPL.

The mean amplitude of the left remaining vocal fold after MFLPL (0.38 ± 0.24 mm) was lower than other reports of excised laryngeal models. This may have been caused by structural unsteadiness and air leakage after the simulative surgery. And excised canine model is not an ideal representation that of patients after FLPL. With the result of this study, we look forward to performing the novel operation on in vivo canine larynges with in vivo phonatory testing as described by Karajanagi et al to get phonation threshold pressures high-speed video data. Following the animal’s sacrifice, excised functional analysis could also be performed.

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Author Contributions
Hongming Xu, study design, data collection, data analysis, manuscript preparation, approval of final version of manuscript; Anton A. Kvit, data collection, data analysis, revision and approval of final version of manuscript; Erin E. Devine, data collection, data analysis, revision and approval of final version of manuscript; Xinjiang Ying, statistical design and analysis, manuscript preparation, approval of final version of manuscript; Pin Dong, study design, manuscript preparation, revision and approval of final version of manuscript.

Disclosures
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