Aerodynamic, Acoustic, and Vibratory Comparison of Arytenoid Adduction and Adduction Arytenopexy

Justin McNamar, MD; Douglas W. Montequin, PhD; Nathan V. Welham, PhD; Seth H. Dailey, MD

Hypothesis: Adduction arytenopexy (AP) with thyroplasty provides improved physiologic placement of the vocal fold and therefore provides improved acoustic, aerodynamic, and vibratory function as compared with arytenoid adduction (AA) with thyroplasty.

Methods: Five cadaveric human larynges were prepared by removing supraglottic tissues and fixing the nontest vocal fold medially on the cricoid facet with a needle in a physiologic phonating position. Each test vocal fold was then sequentially tested using an excised larynx phonation system, first with AA with silastic medialization and then converted to AP without changing the contralateral fold position or silastic wedge. The excised larynx setup allowed for simultaneous collection of data, specifically subglottic pressure (including measurement of phonation threshold pressure [PTP]), mean airflow, acoustic output, and full-frame high-speed digital video.

Results: Aerodynamic evaluation was similar for each group with similar subglottic pressure versus output curves. Conditions involving AP typically had PTP values that were 80% of that for comparable AA conditions. Acoustic evaluation revealed differences between the two groups. Each AA was found to be vibrating with two dominant frequencies with their associated harmonics. Each AP vibrated at a single dominant frequency with its harmonics.

Conclusion: AP provides improved vocal outcomes by decreasing system noise and decreasing PTP, which may lead to a stronger glottal signal with decreased vocal effort.

Key Words: Thyroplasty, arytenoid adduction, arytenopexy.


INTRODUCTION

Laryngeal framework surgery has become the dominant treatment modality for managing symptoms of vocal fold paralysis. Since early descriptions of laryngoplastic surgery, the treatment of vocal fold paralysis has continued to develop. Today, a variety of techniques and implant materials are used to medialize the vocal fold. The majority of patients have very good results with just type 1 thyroplasty. However, there continues to be a subset of patients who have a significant posterior glottal gap, leading to suboptimal voice results including persistent breathy dysphonia and increased vocal effort and fatigue.

Isshiki et al. realized the limitation of solely medializing the vocal fold while not addressing the position of the arytenoid complex in patients with a large posterior glottal gap. By performing an arytenoid adduction (AA) in addition to a type 1 thyroplasty, this gap can be closed, leading to improved vocal outcomes. However, even with an AA, some patients do not have a good vocal outcome. A variety of possibilities regarding arytenoid rotational mechanics have been proposed to explain poor vocal outcomes when using AA, including a shortened and flaccid vocal fold, hyper-rotation of the arytenoid, and improper vocal fold level in the vertical plane.

Zeitels et al. were the first to address these limitations of an AA in their proposal of a new technique, the adduction arytenopexy (AP). By fixing the arytenoid medially on the cricoid facet, the arytenoid is placed in a more physiologic phonating position. Zeitels et al. have noted that the vocal fold is placed in an appropriate vertical plane with improved tension as compared with AA.

Although the AP appears to provide improved vocal position for physiologic phonation, no studies have been performed to compare vocal outcomes. By using cadaveric larynges and an excised larynx phonation system, a variety of glottic parameters and acoustic measures can be directly compared. The goal of this study, therefore, was to compare the acoustic, aerodynamic, and vibratory function of the excised larynges subjected to AA with thyroplasty and AP with thyroplasty.
**TABLE I. Laryngeal Specimen Demographics.**

<table>
<thead>
<tr>
<th>Age</th>
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<td>68</td>
<td>Male</td>
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</table>

**Materials and Methods**

Fresh excised human larynges were obtained from the Department of Pathology, University of Wisconsin School of Medicine and Public Health. Demographic data for each larynx used in the study are supplied in Table I. None of the larynges had any known history of laryngeal pathology or surgery. Specimens were inspected for any evidence of vocal fold mucosal or laryngeal framework injury, and only normal appearing specimens were included in the study. Specimens were initially stored at 4°C in a physiologic concentration of a phosphate-buffered saline solution for a maximum of 36 hours. Specimens were then quick frozen using liquid nitrogen and stored at −80°C until thawed for use.

The same experimental sequence was used in each larynx. Initially, the non-test vocal fold was placed into a physiologic phonating position. This was accomplished by placing a 27-gauge needle vertically through the arytenoid process into the cricoid in a medialized position.

On the test vocal fold, a standard silastic medialization thyroplasty (SMT) was performed followed by an AA. The larynx was then mounted on the excised larynx system while acoustic, aerodynamic, and high-speed imaging data were collected. The AA suture was removed and converted to an AP, leaving the same silastic block in place. The larynx was then rerun on the excised larynx system, obtaining data comparable with the initial data set. The AP had to be performed after the AA because of the disarticulation of the cricoarytenoid joint during AP.

**Laryngeal Preparation**

Excess supraglottic tissue including the epiglottis and false vocal folds was removed to ensure adequate exposure of the vocal folds on the excised larynx setup. The paraglottic tissue and lateral vestibule mucosa were carefully preserved to prevent exposure of the implant, which could impact vocal fold placement.

**Medialization Thyroplasty**

The simulated vocal fold paralysis for this study was treated with SMT. Neither the AA nor AP alone provided adequate vocal fold adduction and therefore required a medialization procedure. The technique used was based on the description by Wannamaker et al.5 A 6 × 13 mm thyroplasty window was created either 5 mm or 7 mm from the anterior commissure in female and male larynges, respectively, while ensuring the preservation of a 3-mm inferior strut. In particularly large larynges, the window length was extended up to 18 mm to obtain proper medialization. The correct depth of the shim was measured based on visual inspection of the vocal folds. An appropriately sized shim was then shaped out of a preformed wedge of silicone block (Medtronic Xomed, Jacksonville, FL). The preformed wedge is shaped such that the point of maximal adduction is at the level of the inferior edge of the thyroplasty window, which limits excessive and unnecessary effacement of the ventricle.

**Arytenoid Adduction**

The AA was completed using a similar technique that originally was described by Isshiki et al.1 A posterior thyroid cartilage window was created to obtain adequate exposure to the arytenoid muscular process. A figure-of-eight stitch using a double-armed 4-0 Prolene (Ethicon, Somerville, NJ) suture was placed in the muscular process and passed anteriorly to the thyroplasty window. The suture was then passed anteriorly through the thyroid window and secured just anteriorly and inferiorly to the anterior edge of the window. Once the silastic block for the accompanying medialization thyroplasty (MT) was in position, the AA suture was tightened until appropriate adduction was obtained.

**Arytenopexy**

The AP was performed as described by Zeitels et al.3 The lateral and posterior cricoarytenoid muscles were elevated off the muscular process of the arytenoid. Subsequently, the cricoarytenoid joint was opened widely. A 4-0 Prolene suture on a cutting needle was passed medially to the facet into the medial portion of the joint space, vertically through the body of the arytenoid anterior to the muscular process, and finally coursing anteriorly to posteriorly through the cricoid cartilage, deep to the facet. The suture was then secured with a slip knot to lock the arytenoid into its new position.

**Excised Larynx Phonation System**

To test the passive vibratory mechanics when comparing AA and AP, each larynx was mounted on an air tube system that simulates the biological function of expiration by delivering heated and humidified air at defined pressure and flow rates. The trachea of the excised larynx was fixed to the tube using a hose clamp to eliminate air leakage. To help maintain the larynx in a fixed position for superior view visualization, a specialized ring holder with pins was used to provide structural support to the thyroid and cricoid cartilages.

Pressurized air was warmed and humidified using a humidifier controller (3M, St. Paul, MN). Subglottal pressure and glottal flow were monitored with a Dwyer Instruments (Michigan City, IN) U-tube manometer (range 0–100 cm H2O) and a flowmeter (Gilmont Instruments, Barrington, IL) (range 0–60 L/m). The acoustic signal was monitored with an Omnidyne 578 omnidirectional dynamic microphone (Shure Inc., Niles, IL) (placed at 45°, 15 cm from the glottis) and Blueteue preamplifier (PreSonu Audio Electronics, Inc., Baton Rouge, LA), and intensity was monitored with a RadioShack (Fort Worth, TX) digital sound level meter (also placed at 45°, 15 cm from the glottis). Images of vocal fold vibration were captured using a Kodak Ektapro HS Motion Analyzer 4540 (Eastman Kodak, Rochester, NY) (up to 4,500 frames/sec) that was positioned superiorly to the glottis and controlled by a personal computer using a GPIB instrument controller card and IMAQ image acquisition card (National Instruments, Austin, TX). Four experimental signals were digitally collected using a second personal computer running a Dataq DL-720 analog-digital converter and WinDaq 2.72 data acquisition software (Dataq Instruments, Akron, OH) (each signal was digitized at 30 kHz): 1) subglottal pressure, measured using a PK8772-4 microswitch pressure transducer (Honeywell, Morris-town, NJ); 2) glottal airflow, measured using a Fleish pneumotachograph combined with a DP-103 pressure transducer (Validyne Engineering, Northridge, CA); 3) acoustic signal, measured using the aforementioned microphone and preamplifier; and 4) motion analyzer trigger, used for synchronization of video data to the other three digital signals.

Analysis was completed using a personal computer and MATLAB (Mathworks, Natick, MA), a commercial engineering software package. Programs were written and modified as needed.
for each specific experimental task. Acoustic analysis included decomposing the recorded acoustic signal into its sinusoidal components using a fast Fourier transform (FFT). These components were then used to identify the dominant or fundamental frequency for each vibrating larynx and the associated harmonics. From high-speed video data, amplitude of vibration of each individual vocal fold, maximum glottal area, and minimum glottal area data were obtained from two representative vibratory cycles of each run.

RESULTS
A total of five larynges were tested in this study. One larynx did not adequately vibrate after AA but did vibrate well after AP. The remaining four larynges vibrated well with physiologic subglottic pressures after both AA and AP. Aerodynamic evaluation found AP to have a lower phonation threshold pressure (PTP) than AA in three of the four larynges (Table II). In the fourth larynx, PTP was essentially the same. Statistical testing using a Wilcoxon signed rank test revealed nonsignificant differences in PTP between the AA and AP groups ($P = .38$). Glottal resistance and output-cost ratio (OCR) plots were nearly identical for each larynx, with each procedure indicating similar aerodynamic performance (Fig. 1). Again, statistical testing using a Wilcoxon signed rank test was nonsignificant (glottal resistance, $P = .63$; OCR, $P = .25$).

During acoustic analysis, the FFT of each AA larynx revealed two independent dominant frequencies with their associated harmonics, introducing significant “noise-like” signal information. However, in each larynx after AP, only a single fundamental frequency and its associated harmonics were identified, providing a more “clear” signal. Figure 2 contains FFT data for each larynx after AA and AP.

High-speed imaging was used to evaluate vocal fold vibratory symmetry. A ratio of the treated vocal fold versus the nontest vocal fold amplitude was calculated (Table III). A ratio closer to 1 indicates more symmetric vocal fold vibratory motion. The AA group had an average ratio of $0.81 \pm 0.16$ versus $0.98 \pm 0.14$ in the AP group. Evaluation using a Wilcoxon signed rank test revealed no significant differences ($P = .20$).

Table III also includes visual interpretation of the vibratory symmetry of each laryngeal run. Greater vibratory asymmetry and aperiodicity were noted in the AA condition. This asymmetry was generally characterized by near-20 vibratory mode (i.e., 2 independent vibratory modes operating in the anterior and posterior membranous vocal folds, with near-0 vibratory amplitude at the mid-membranous glottis), which contrasted with the normal appearing 10-mode vibration (i.e., a single predominant vibratory mode with maximum amplitude at the mid-membranous glottis) observed in the AP condition.

DISCUSSION
MT has become the dominant technique to treat unilateral vocal fold paralysis. In the majority of patients, it is very successful and leads to favorable functional voice outcomes.6–9 However, certain patients have a persistent posterior glottic gap that limits phonatory outcome success. The results of this study suggest that AP may place the vocal fold in an improved physiologic position compared with AA.

The AA proposed by Isshiki et al.2 was the first attempt to address this problem and close a posterior glottal gap. Several retrospective studies have been performed to subjectively test vocal outcomes after AA with MT versus only MT. Bielamowicz et al.10 performed objective voice analysis between these two groups and did not find any differences in jitter, shimmer, harmonics to noise ratio, airflow, or subglottal pressure. No studies have reported statistically significant differences in vocal outcomes between these two groups. In fact, Chester and Stewart11 performed an evidence-based review of the literature to compare AA with MT versus MT only and found very
Fig. 2. Fast Fourier transform after arytenoid adduction (AA) and adduction arytenopexy (AP). AA was noted to have two fundamental frequencies and associated harmonics compared with just a single fundamental frequency after AP. The fundamental frequencies and predicted harmonics are marked by the squares and circles.
limited evidence to support or reject the use of AA in combination with MT in place of MT alone. However, true comparison of these two groups may not be possible in that AA is designed to manage a different mechanical problem for glottal closure, and therefore AA and MT should not be considered interchangeable. The AA procedure is designed to close a posterior glottal gap, which is not necessarily present in the majority of patients with glottal insufficiency. Other studies reviewing outcomes after AA with MT have shown good benefit.\textsuperscript{12–14}

<table>
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<th>Amplitude of Vibration (Treated) (mm)</th>
<th>Ratio of Treated/Nontest</th>
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Last column is visual interpretation of closure pattern.
VF = vocal fold; AA = arytenoid adduction; AP = adduction arytenopexy.

AA may not be the best method to close a posterior glottal gap. The AA suture does not simulate all of the dynamic action of the lateral cricoarytenoid muscle and other intrinsic muscles of the larynx, and thus it tends to place the arytenoid in a nonphysiologic anterior-inferior and hyper-rotated position on the cricoid facet. The anterior displacement limits the degree of length and subsequent tension that can be placed on the vocal fold. The inferior displacement affects the vertical level of the vocal fold, often preventing correct approximation with the...
contralateral vocal fold in the superior-inferior plane. Woodson et al.\textsuperscript{15,16} discussed this vertical closure pattern problem with AA and advocated adding a second suture to try to further adjust vocal fold position.

Zeitels et al.\textsuperscript{3} also have voiced concerns regarding a positioning problem with AA, pointing out that “effective vocal fold vibration (optimal voice) requires that the im-

The arytenoid medially on the facet, there was an

Their cadaveric studies demonstrated a longer membra-

AP to close the posterior gap while placing the

This led Zeitels et al. to propose AP to close the posterior gap while placing the

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arytenoid in a physiologic position on the cricoid facet. Their cadaveric studies demonstrated a longer membra-

arytenoid in a physiologic position on the cricoid facet. Their cadaveric studies demonstrated a longer membra-

their finding was likely caused by a more physiologically correct placement of the arytenoid in 1.8 mm. Zeitels et al.\textsuperscript{4} have reported that preoperative and postop-

are comparable with previously published laryngeal frame-

work surgery results.

The goal of the current study was to compare aerody-

amic, acoustic, and vibratory results of AA versus AP. By using cadaveric larynges and performing both AA and AP on the same larynx, these procedures could be compared with themselves (intraspecimen) rather than with a second group of larynges (interspecimen). This style of comparison helps eliminate some problems related to laryngeal heterogeneity. Because both AA and AP effectively close the posterior gap, it is not surprising that many of the aerodynamic results were very similar. Lower PTP was observed in three of four larynges; however, statistical significance was not reached, probably because of the small number of larynges studied.

More interesting findings were noted, however, in the acoustic analysis data. With all four larynges after AA, there were two separate dominant frequencies with their associated harmonics. In sharp contrast, there was only a single dominant (fundamental) frequency with its associated harmonics in each of the five larynges after AP. This finding was likely caused by a more physiologically correct placement of the paralyzed vocal fold under the AP condition, for several reasons. In the postsurgical medialization patient, phonation is completed using one vocal fold with appropriate active and passive biomechanical tension from appropriate innervation, allowing prephonatory vocal fold posturing, whereas the contralateral fold is primarily under passive biomechanical tension only. In the excised larynx setup, all active muscle properties are elimi-

ated, allowing direct comparison of the passive biome-

chanical properties of AA and AP. It appears, then, that the passive biomechanical properties and prephonatory postures are better matched symmetrically with AP compared with AA. Having a more appropriate symmetrical configuration with respect to glottal closure and prephonatory posturing helps explain why the AP procedure resulted in a clearer acoustic signal.

By limiting vertical phase mismatch of the vocal folds, AP helps to entrain vocal fold vibration, yielding a single fundamental frequency. Vertical mismatch after AA acts to constrain adaptive entrainment, allowing the vocal folds to function more as separate vibratory sources, thus explaining the two dominant frequencies observed here.

This study holds certain limitations. The small number of larynges limited the statistical power of the study and contributed to the lack of significance observed during statistical testing. Also, AP had to be performed as the final procedure because of disarticulation of the cricoarytenoid joint. It is possible that the manipulation and testing performed under the AA condition may have impacted the pho-

notory characteristics measured in the AP condition.

In conclusion, it appears that AP results in a more symmetrically entrained vocal fold vibratory pattern than AA, when considering only passive biomechanics, leading to a likely possible decrease in vocal effort and increase in signal to noise ratio in vocal output. As a result, it appears likely that differences in surgical success using AA versus AP can be related to passive mechanical properties such as prephonatory shape and passive glottal tension symmetry. It is not clear from this study how significant the differences between AA and AP are when introducing active biomechanical properties of the healthy vocal fold. Increases in vocal output noise correlate well with poor vocal fold entrainment. As a result, it is suggested that either surgical procedure can be successful in improving aerodynamic, acoustic, and vibratory parameters in the pathologic voice related to vocal cord paralysis as long as basic symmetry in prephonatory geometry and gross vocal fold tension is preserved/restored.

Acknowledgments

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BIBLIOGRAPHY


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