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Optimal arytenoid adduction based on quantitative real-time voice analysis

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Abstract

Hypothesis—The optimal degree of arytenoid rotation for arytenoid adduction (AA) can be determined using quantitative real-time voice analysis.

Study design—Repeated measures with each larynx serving as its own control.

Methods—Unilateral vocal fold paralysis (VFP) was modeled in five excised canine larynges. Medialization laryngoplasty (ML) was performed, followed by AA. The optimal degree of arytenoid rotation was determined using real-time measurements of vocal efficiency (V_E), percent jitter, and percent shimmer. After the optimal degree of rotation was determined, the arytenoid was hypo- and hyper-rotated $10 \pm 2\%$ of the optimal angle to mimic hypoadducted and hyperadducted states. Aerodynamic, acoustic, and mucosal wave measurements were recorded.

Results—Mean optimal angle of arytenoid adduction was $151.4 \pm 2.5^\circ$. V_E differed significantly across experimental conditions ($p = 0.003$). Optimal AA produced the highest V_E of any treatment, but this value did not reach that produced in the normal condition. Percent jitter ($p < 0.001$) and percent shimmer ($p < 0.001$) differed across groups and were lowest for optimal AA. Mucosal wave amplitude of the normal ($p = 0.001$) and paralyzed fold ($p = 0.043$) differed across treatments. Amplitude of both folds was highest for optimal AA.

Conclusions— V_E and perturbation parameters were sensitive to the degree of arytenoid rotation. Using real-time voice analysis may aid surgeons in determining the optimal degree of arytenoid rotation when performing AA. Testing this method in patients and determining if optimal vocal outcomes are associated with optimal respiratory and swallowing outcomes will be essential to establishing clinical viability.

Evidence based medicine level—Not applicable – excised animal tissue study.

Keywords

arytenoid adduction; vocal fold paralysis; medialization laryngoplasty; laryngeal framework surgery

INTRODUCTION

Arytenoid adduction (AA) was introduced by Isshiki et al. as an additional treatment for vocal fold paralysis (VFP), primarily indicated for patients with a wide glottal chink or

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bilateral superoinferior vocal fold asymmetry.¹ Sutures passed from the muscular process of the arytenoid through the thyroid cartilage can simulate the contractile forces of the lateral cricoarytenoid and thyroarytenoid muscles, medializing a paralyzed fold when tension is placed on the suture. Due to the cylindrical shape of the cricoarytenoid joint,¹ the vocal process moves downward during adduction and can correct a difference in the levels of the vocal folds by lowering the affected fold.²

Though the procedure has shown great utility and can effectively decrease a wide posterior glottal gap, surgical success of the procedure is inconsistent.³ Determination of optimal adduction is based on empirical judgments made during intraoperative voicing, a subjective and potentially time-consuming method which does not consistently yield optimal results.³ Locating and manipulating the muscular process is also difficult, giving the procedure a high level of technical difficulty⁴ and decreasing the frequency with which it is performed.

When performed correctly, AA can produce dramatic improvement in laryngeal function. In a study retrospectively comparing patients undergoing medialization laryngoplasty (ML) and simultaneous ML-AA, patients undergoing ML-AA had significantly better vocal improvement as evaluated by the GRBAS rating scale and patient satisfaction.⁵ ML is limited by an inability to close a wide posterior glottal chink and correct a difference in the horizontal plane of the vocal folds. This is due to the posterior glottis and arytenoids residing outside the paraglottic space affected by the thyroplasty implant.⁵

One of the more common complications reported from AA is airway compromise.^{6,7} This can be attributed to overrotation of the arytenoid and consequent hyperadduction of the vocal fold beyond the glottal midline. Such hyperadduction compromises vocal outcomes as well, resulting in a pressed vocal quality. Dysphagia has also been reported following AA,⁸ possibly due to hypoadduction and consequent residual glottis insufficiency. Due to the increased morbidity associated with AA, some authors question whether the procedure is warranted;⁹ however, the added improvement of AA after ML provides support for its use.¹⁰ Developing an objective, quantitative evaluation may allow surgeons to more efficiently and accurately evaluate the degree of adduction, maximizing procedural benefit and reducing risk. We employed real-time measures of percent jitter, percent shimmer, and vocal efficiency (V_E) to determine the optimal degree of arytenoid rotation in an excised larynx setup. We also examined mucosal wave characteristics to determine if this optimal degree of rotation produced the greatest improvement in vocal fold vibration.

MATERIALS AND METHODS

Larynges

Five larynges were excised postmortem from canines sacrificed for non-research purposes according to the protocol described by Jiang and Titze.¹¹ As the size and histological properties of the canine and human larynx are similar,¹² it is an appropriate model for studying human laryngeal physiology. Larynges were examined for evidence of trauma or disorders; any larynges exhibiting trauma or disorders were excluded. Following visual inspection, larynges were frozen in 0.9% saline solution.

Apparatus

Prior to the experiment, the epiglottis, corniculate cartilages, cuneiform cartilages, and ventricular folds were dissected away to expose the true vocal folds. The superior cornu and posterosuperior part of the thyroid cartilage ipsilateral to the normal vocal fold were also dissected away to facilitate insertion of a lateral 3-pronged micrometer into the arytenoid cartilage. The larynx was mounted on the apparatus (figure 1) as specified by Jiang and Titze.¹¹ A metal pull clamp was used to stabilize the trachea to a tube connected to a

pseudolung which served as a constant pressure source. Insertion of one 3-pronged micrometer in the arytenoid cartilage ipsilateral to the dissected thyroid cartilage allowed for adduction of one vocal fold, simulating UVFP in the unadducted vocal fold as in Czerwonka et al.,¹³ Witt et al.,¹⁴ and Hoffman et al.¹⁰ An additional 3-pronged micrometer was placed against the contralateral thyroid lamina for stability without providing vocal fold adduction. Methodological consistency was maintained by always adducting the contralateral arytenoid (simulated normal) to the midline. Micrometer positioning remained constant across sets of trials within the same larynx. Tension on the vocal folds and control of vocal fold elongation was accomplished by attaching the superior anteromedial thyroid cartilage, just inferior to the thyroid notch, to an anterior micrometer. Vocal fold elongation and adduction remained constant for all trials.

The pseudolung used to initiate and sustain phonation in these trials was designed to simulate the human respiratory system. Pressurized airflow was passed through two Concha Therm III humidifiers (Fisher & Paykel Healthcare Inc., Laguna Hills, California) in series to humidify and warm the air. The potential for dehydration was further decreased by frequent application of 0.9% saline solution between trials. Airflow was controlled manually and was measured using 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).

Acoustic data were collected using a dbx microphone (model RTA-M, dbx Professional Products, Sandy, Utah) positioned at a 45° angle to the vocal folds. The microphone was placed 10 cm from the glottis to minimize acoustic noise produced by turbulent airflow. Acoustic signals were subsequently amplified by a Symetrix preamplifier (model 302, Symetrix Inc., Mountlake Terrace, Washington). A National Instruments data acquisition board (model AT-MIO-16; National Instruments Corp, Austin, Texas) and customized LabVIEW 8.5 software were used to record airflow, pressure, and acoustic signals on a personal computer. Aerodynamic data were recorded at a sampling rate of 100 Hz and acoustic data at 40,000 Hz. Experiments were conducted in a triple-walled, sound-proof room to reduce background noise and stabilize humidity levels and temperature.

The vocal fold mucosal wave was recorded for approximately 200 milliseconds per trial using a high-speed digital camera (model Fastcam-ultima APX; Photron, San Diego, CA). Videos were recorded with a resolution of 512×256 pixels at a rate of 4000 Hz.

Experimental Methods

Trials were conducted as a sequence of 5 second periods of phonation, followed by 5 second periods of rest. Five trials were performed for each condition. During each trial, airflow passing through the larynx was increased gradually and consistently until the onset of phonation. All procedures were performed by the same author (MRH) under the supervision of the senior author (TMM). Larynges were thoroughly hydrated with saline solution between trials and between sets of trials to eliminate any potentially confounding effects of dehydration.

ML was performed using a Silastic implant (Dow Corning Corporation, Midland, MI). The implant was inserted through a 6×11 mm thyroplasty window in the thyroid cartilage ipsilateral to the paralyzed vocal fold. AA was performed after a set of trials was conducted analyzing the effect of ML. The procedure was performed according to the clinical descriptions by Isshiki.¹ One suture was passed with a needle from the muscular process of the arytenoid anteriorly through the paraglottic space through the thyroid cartilage just lateral to the anterior commissure and the second inferior to the cartilage was tightened to

rotate the arytenoid and adduct the simulated paralyzed fold. The optimal degree of rotation was determined using real-time measurements of V_E primarily and percent jitter and percent shimmer secondarily. After trials were performed at the optimal degree of rotation, the arytenoid was hypo- and hyper-rotated $10 \pm 2\%$ of the optimal angle created by the glottal axis and medial aspect of the arytenoid ipsilateral to the simulated paralyzed fold (figure 2).

Data Analysis

Airflow and pressure at the phonation onset were recorded as the phonation threshold flow (PTF) and phonation threshold pressure (PTP), respectively. Phonation threshold power (PTW) was calculated as the product of these values. PTF, PTP, and PTW were determined manually using customized LabVIEW 8.5 software.

Measured acoustic parameters included frequency, signal-to-noise ratio (SNR), percent jitter, and percent shimmer. Acoustic signals were trimmed using GoldWave 5.1.2600.0 (GoldWave Inc., St. John's, Canada) and analyzed using TF32 software (Madison, WI).

High speed video recordings of the mucosal wave were analyzed using a customized MATLAB program (The MathWorks, Natick, MA). Vibratory properties of each of the four vocal fold lips (right-upper, right-lower, left-upper, left-lower) were quantified via digital videokymography (VKG). Threshold-based edge detection, manual wave segment extraction, and non-linear least squares curve fitting using the Fourier Series equation were applied to determine the most closely fitting sinusoidal curve. This curve was used to derive the amplitude and phase difference of the mucosal wave of each vocal fold lip, both before and after treatment. Interfold phase difference was calculated as the phase difference between the right upper and left upper vocal fold lips while intrafold phase difference was calculated as the phase difference between the upper and lower lips of the right (paralyzed) vocal fold. Mucosal wave amplitude was calculated as the average of the amplitudes of the upper and lower paralyzed vocal fold lips. While only relative rather than absolute values could be obtained due to current technological limitations, this was sufficient for the treatment comparisons performed in this study.

Statistical analysis

One-way repeated measures analysis of variance (ANOVA) was performed to determine if parameters changed across the six experimental conditions (normal, paralyzed, ML, hypoadducted AA, optimal AA, and hyperadducted AA). If data were not normal according to a Shapiro-Wilk test or did not display equal variance according to a Levene's test, ANOVA on ranks was performed. Paired t-tests were performed on each possible condition pairing to further analyze potential differences in each parameter measured. If data did not meet assumptions for parametric testing, a Wilcoxon-Mann-Whitney rank sum test was used. Tests were two-tailed and a significance level of $\alpha=0.05$ was used for all statistical tests.

RESULTS

Optimal angle of arytenoid adduction

Mean optimal angle of arytenoid adduction was $151.4 \pm 2.5^\circ$. The arytenoid was then hypo- and hyper-rotated to mean angles of $161.6 \pm 11.2^\circ$ and $143.4 \pm 13.5^\circ$, respectively. Summary aerodynamic, acoustic, and mucosal wave data are presented in tables I, II, and III. Results from paired t-tests are provided in table IV.

Aerodynamics

PTF ($p < 0.001$) and PTW ($p = 0.011$) differed significantly across treatment groups, while PTP did not ($p = 0.193$). PTF, PTP, and PTW were lowest for the optimal AA treatment. V_E also differed significantly across treatments ($p = 0.003$). Optimal AA produced the highest V_E of any treatment, and was insignificantly less than for normal (figure 3) ($p = 0.625$). The differences in V_E relative to the other treatments approached, but did not reach significance (table IV).

Acoustics

Percent jitter ($p < 0.001$), percent shimmer ($p < 0.001$), and SNR ($p < 0.001$) differed significantly across treatment groups. Percent jitter and percent shimmer for optimal AA were the lowest for any treatment (figures 4, 5). Perturbation was significantly lower for optimal AA compared to ML, and discernibly lower compared to hypo- and hyperadducted AA (table IV). The percent shimmer for optimal AA was also lower than that for the normal condition, though this difference was not significant. Frequency differed significantly across treatment groups ($p = 0.017$) and was highest for the normal condition. SNR was highest for the normal condition, but this was not significantly greater than the SNR produced by any of the AA conditions (table IV).

Mucosal wave

Amplitude of the normal fold ($p = 0.001$) and paralyzed fold ($p = 0.043$) differed significantly across treatment groups. No significant changes occurred for intrafold ($p = 0.303$) or interfold phase difference ($p = 0.973$). Amplitude of both the left (simulated normal) and right (simulated paralyzed) folds decreased significantly upon simulating the paralyzed condition. Optimal AA produced the greatest amplitude for both folds (figure 6).

DISCUSSION

We present a quantitative method for determining the optimal degree of arytenoid rotation when performing AA using real-time voice measurements. This is a preliminary study establishing the validity of this method and the sensitivity of the chosen measures to small changes in arytenoid position. Ex vivo canine larynges have been used extensively to study vocal fold paralysis.^{10,12-14} There are several anatomical differences in the canine larynx relative to the human, including more angulated thyroid and cricoid cartilages, and the absence of a well-defined vocal ligament.¹² These differences did not affect the procedures performed in this study.

This is our second study examining the added benefit of performing AA after ML in excised canine larynges.¹⁰ By optimizing the degree of arytenoid rotation, we observed even greater changes in all parameters of interest. While assessing the added benefit of AA following ML in patients can be difficult as the two procedures are often performed simultaneously, this can easily be done using the excised larynx setup. Our results provide additional support for the use of AA in patients who can tolerate it.

Aerodynamic parameters behaved as expected, with increases in PTF and PTP occurring in the simulated paralysis condition, and stepwise decreases occurring from paralysis to ML to AA. As observed previously,^{10,14} PTF varied significantly across treatments while PTP did not. PTF is directly related to the cube of neutral glottal half-width¹⁵ and is more sensitive than PTP to changes in glottal abduction.¹⁶ While the threshold parameters displayed differences across the three AA conditions, the differences were not as evident as for perturbation parameters or V_E . Accurate measurement of threshold aerodynamics,

particularly PTF, also remains a challenge. PTP and PTF, therefore, are likely not suitable parameters for intraoperative voice assessment.

Perturbation parameters, however, may offer a more reliable and feasible alternative for determining optimal arytenoid rotation. Recording requires only a microphone and software equipped with the real-time measurement employed in this study. Percent jitter and percent shimmer were both sensitive to arytenoid position, with the optimal AA angle producing the lowest values. Fundamental frequency was significantly lower for the AA conditions relative to normal, but this may be a result of the experimental design. Phonation tokens were recorded at the phonation threshold. As PTP was lowest in the AA conditions and pressure has a direct relationship with frequency, fundamental frequency was lower. A decrease in F_0 following AA has also been reported previously.¹⁷ Increases in SNR can be attributed to decreased flow (noise) as well as increased sound production (signal), with optimal AA producing the most dramatic improvement. Real-time intraoperative measurements of SNR may not be beneficial though, as an extremely hyperadducted larynx would have a high SNR due to minimal flow escaping the glottis.

Changes in mucosal wave amplitude were of particular interest, as dramatic changes occurred across the three AA conditions for both folds (table III). Real-time mucosal wave analysis is currently not feasible due to the laborious nature of extracting parameters from a segment of high speed video. As extraction and analysis techniques are improved, real-time mucosal wave amplitude analysis may offer another means of determining the optimal degree of arytenoid rotation. Intrafold phase difference reflects the presence or absence of a normal mucosal wave. Ideally, there should be a phase difference of π between the upper and lower lips of the vocal fold. A phase difference similar to this was observed in both the normal and optimal AA conditions. Thus, the optimal degree of arytenoid rotation produced the greatest improvements in vocal fold vibratory characteristics. Intrafold phase difference was decreased in the other conditions. There did not appear to be a pattern for change in interfold phase difference across conditions.

Differences in V_E and perturbation parameters across the three AA conditions were not significant; however, significant differences were not expected for the subtle changes in arytenoid position that were analyzed. The primary objective of this study was to demonstrate that V_E and perturbation parameters were sensitive to changes in arytenoid rotation, increasing and decreasing, respectively, until the optimal degree of rotation was reached. As the differences did approach significance, particularly for V_E , one could anticipate that significant differences may be found with a larger sample size.

V_E was used with success in this study to distinguish among subtle differences in arytenoid rotation when performing AA. It may be potentially more useful than perturbation parameters as it evaluates both aerodynamics, the input to voice production, and acoustics, the output. For several other measured parameters such as percent jitter and threshold aerodynamics, hyperadducted AA performed rather similarly to optimal AA. However, there was over a four-fold increase in V_E for optimal AA compared to hyperadducted AA (table I, figure 3). As hyperadduction can lead to postoperative dyspnea, it is important to measure parameters which vary significantly with subtle changes in arytenoid rotation. V_E , therefore, may represent the most useful parameter for determining the optimal degree of arytenoid rotation during AA.

Both V_E and perturbation parameters can be measured intraoperatively. Measuring perturbation parameters would be easier, as it would require only a microphone and the software used in this study. Measurement of V_E could be done using the airflow interrupter,¹⁸ which uses a mechanical balloon valve to interrupt sustained phonation.

Airflow interruption has been used with success to assess disordered subjects¹⁹ and could be applied to patients with VFP. This method would require more patient cooperation than measurement of perturbation parameters. Alternatively, aerodynamic measures could be obtained directly via a cricothyroid membrane puncture. This, coupled with acoustic measurements obtained with a microphone, could also be used to measure V_E . Patients would then need only to produce a sustained vowel for all measurements to be recorded. Evaluating both V_E and perturbation parameters clinically would be valuable to determine which can adequately distinguish among different degrees of arytenoid rotation while minimizing demands on patient vocal effort. The degree to which the implementation of each increases operative time must also be analyzed. Intraoperative edema resultant from increased operative time may confound measurement and lead to an arytenoid position which is not optimal. Real-time voice analysis also has the ability to reduce intraoperative edema, as it eliminates potentially time-consuming subjective voice assessment. A surgeon can rotate the arytenoid along an arc until V_E stops increasing and perturbation measures stop decreasing. This point would not be found as easily if using subjective voice assessment.

It is also important to evaluate the use of real-time voice measurements in patients to determine if optimal vocal outcomes are associated with optimal respiratory and swallowing outcomes. AA has been associated with improvement in voice, swallowing, and respiratory function;⁶ however, examining swallowing and respiratory function after performing AA with real-time voice measurements is necessary if this method is to be applied clinically. One limitation of the excised larynx setup is that only vocal function can be analyzed. The angle we found to be optimal may be slightly more acute than what would be optimal for the larynx of a human patient. Though the paralyzed vocal fold was adducted just past the midline (figure 2b), this degree of adduction may be sufficient to cause episodic dyspnea. This concern must be considered when utilizing intraoperative voice analysis. Future investigations will focus on balancing the desire for a good vocal outcome with the need for a good respiratory outcome.

CONCLUSION

Real-time measurements of vocal efficiency and perturbation parameters are proposed to guide surgeons when performing arytenoid adduction. Testing in an excised larynx setup demonstrated that these measurements are sensitive to the degree of arytenoid rotation. Rotating the arytenoid until vocal efficiency stops increasing and perturbation parameters stop decreasing may yield the optimal arytenoid position for voice production. Determining if optimal vocal outcomes are associated with optimal respiratory and swallowing outcomes will be essential to establishing the clinical viability of this method.

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Figure 1.
Schematic diagram of the excised larynx experimental bench apparatus.

Figure 2. Angle created by glottal axis and medial aspect of arytenoid cartilage which was used to define the degree of arytenoid rotation. The optimal angle (B) was determined using real-time voice measurements. The arytenoid was then hypo- (A) and hyper-rotated (C) to mimic hypoadducted and hyperadducted states.

Figure 3. Vocal efficiency (V_E) across experimental conditions. Error bars represent standard error. VFP = vocal fold paralysis; ML = medialization laryngoplasty; hypo AA = hypoadducted arytenoid adduction; optimal AA = optimal arytenoid adduction; hyper AA = hyperadducted arytenoid adduction.

Figure 4. Percent jitter across experimental conditions. Error bars represent standard error. VFP = vocal fold paralysis; ML = medialization laryngoplasty; hypo AA = hypoadducted arytenoid adduction; optimal AA = optimal arytenoid adduction; hyper AA = hyperadducted arytenoid adduction.

Figure 5. Percent shimmer across experimental conditions. Error bars represent standard error. VFP = vocal fold paralysis; ML = medialization laryngoplasty; hypo AA = hypoadducted arytenoid adduction; optimal AA = optimal arytenoid adduction; hyper AA = hyperadducted arytenoid adduction.

Figure 6. Kymographs from each experimental condition: normal (A); paralyzed (B); medialization laryngoplasty (C); hypoadducted arytenoid adduction (D); optimal arytenoid adduction (E); hyperadducted arytenoid adduction (F).

Table 1

Summary aerodynamic data presented as mean $\pm$ standard deviation (n=5).

Parameter	Normal	VFP	ML	Hypo AA	Optimal AA	Hyper AA	P-value
PTF	25.9 (23.4)	76.0 (50.6)	87.9 (67.9)	26.4 (58.8)	15.2 (21.8)	27.6 (22.3)	<0.001
PTP	10.8 (8.79)	13.0 (10.4)	13.3 (10.5)	7.31 (5.24)	7.56 (3.10)	7.56 (5.73)	0.193
PTW	279 (553)	990 (1414)	1328 (1588)	203 (706)	97.8 (208)	127 (212)	0.011
V _E	3.7E-06 (6.9E-05)	1.3E-07 (2.7E-07)	8.6E-08 (1.9E-07)	1.0E-06 (7.4E-06)	3.0E-06 (2.0E-05)	1.0E-06 (4.2E-06)	0.003

A significance level of $\alpha=0.05$ was used for all tests. PTF = phonation threshold flow (ml/s); PTP = phonation threshold pressure (cmH₂O); PTW = phonation threshold power (ml/s * cmH₂O); V_E = vocal efficiency (units); VFP = vocal fold paralysis; ML = medialization laryngoplasty; hypo AA = hypoadducted arytenoid adduction; optimal AA = optimally adducted arytenoid adduction; hyper AA = hyperadducted arytenoid adduction. Values are presented as median (interquartile range).

Table II

Summary acoustic data presented as mean $\pm$ standard deviation (n=5).

Parameter	Normal	VFP	ML	Hypo AA	Optimal AA	Hyper AA	P-value
% Jitter	0.762 (1.33)	5.09 (3.62)	4.24 (1.43)	2.27 (2.67)	0.815 (1.48)	1.10 (5.33)	<0.001
% Shimmer	3.96 (3.41)	28.8 (12.7)	32.2 (19.3)	9.95 (13.9)	4.85 (3.25)	4.23 (5.18)	<0.001
SNR	16.1 (8.0)	11.5 (7.7)	4.09 (4.8)	23.7 (22.9)	22.7 (15.7)	19.3 (16.2)	<0.001
F ₀ (Hz)	215 (117)	174 (58)	237 (168)	159 (177)	149 (75)	169 (75)	0.017

A significance level of $\alpha = 0.05$ was used for all tests. SNR = signal-to-noise ratio; F₀ = fundamental frequency; VFP = vocal fold paralysis; ML = medialization laryngoplasty; hypo AA = hypoadducted arytenoid adduction; optimal AA = optimally adducted arytenoid adduction; hyper AA = hyperadducted arytenoid adduction. Values are presented as median (interquartile range).

Table III

Summary mucosal wave data presented as mean ± standard deviation (n=8).

Parameter	Normal	VFP	ML	Hypo AA	Optimal AA	Hyper AA	P-value
Amplitude (L)	8.41 (8.25)	3.39 (1.71)	1.35 (2.52)	2.52 (2.47)	8.21 (4.83)	5.78 (7.52)	0.001
Amplitude (R)	7.48 (5.27)	4.99 (2.63)	3.51 (2.33)	4.50 (2.49)	8.42 (7.19)	7.18 (5.20)	0.043
Intrafold ΔΦ	3.20 (5.20)	-0.044 (5.09)	-0.224 (4.97)	-0.311 (5.57)	0.424 (7.62)	0.475 (1.20)	0.303
Interfold ΔΦ	-0.603 (4.31)	0.228 (2.45)	0.405 (3.73)	0.816 (3.11)	0.761 (2.21)	0.043 (6.38)	0.973

A significance level of $\alpha = 0.05$ was used for all tests. Amplitude (L) = amplitude of left vocal fold (simulated normal); amplitude (R) = amplitude of right vocal fold (simulated paralyzed); intrafold $\Delta\Phi$ = phase difference between upper and lower lips of right vocal fold; interfold $\Delta\Phi$ = phase difference between upper lips of left and right folds; VFP = vocal fold paralysis; ML = medialization laryngoplasty; hypo AA = hypoadducted arytenoid adduction; optimal AA = optimally adducted arytenoid adduction; hyper AA = hyperadducted arytenoid adduction. Amplitude and phase difference have arbitrary units. Values are presented as median (interquartile range).

Table IV
P-values from paired t-tests comparing acoustic, aerodynamic, and mucosal wave parameters for all possible condition pairings.

Comparison	PTF	PTP	PTW	V _E	% Jitter	% Shimmer	SNR	F ₀	Amplitude R	Amplitude L	Interfold $\Delta\Phi$	Intrafold $\Delta\Phi$
Normal, VFP	0.009	0.481	0.092	0.063	0.018	0.011	0.116	0.142	0.25	0.028	0.628	0.398
Normal, ML	0.012	0.014	0.034	0.063	<0.001	0.011	0.012	0.4	0.247	0.039	0.765	0.26
Normal, Hypo AA	0.448	0.652	0.827	0.125	0.215	0.289	0.526	0.033	0.445	0.037	0.637	0.331
Normal, Optimal AA	0.847	0.27	0.813	0.625	0.8	0.873	0.334	0.063	0.363	0.943	0.903	0.8
Normal, Hyper AA	0.895	0.553	0.625	0.188	0.5	0.559	1	0.036	0.927	0.611	0.726	0.481
VFP, ML	0.928	0.679	0.727	0.56	0.327	0.956	0.293	0.387	0.659	0.284	0.827	0.619
VFP, Hypo AA	0.064	0.337	0.216	0.125	0.062	0.199	0.178	0.92	0.827	0.51	0.881	0.539
VFP, Optimal AA	0.011	0.114	0.052	0.063	0.021	0.015	0.07	0.131	0.016	0.059	0.061	0.194
VFP, Hyper AA	0.009	0.342	0.06	0.063	0.03	0.032	0.147	0.204	0.247	0.152	0.734	0.633
ML, Hypo AA	0.043	0.229	0.173	0.125	0.046	0.043	0.073	0.169	0.113	0.107	0.889	0.635
ML, Optimal AA	0.012	0.075	0.061	0.063	0.004	0.006	0.063	0.125	0.008	0.022	0.608	0.125
ML, Hyper AA	0.016	0.209	0.06	0.063	0.01	0.005	0.063	0.057	0.033	0.017	0.849	0.18
Hypo AA, Optimal AA	0.063	0.438	0.063	0.063	0.119	0.206	0.513	0.349	0.027	0.023	0.11	0.125
Hypo AA, Hyper AA	0.341	0.955	0.813	0.313	0.334	0.254	0.647	0.3	0.056	0.03	0.775	0.215
Optimal AA, Hyper AA	0.69	0.28	0.661	0.125	0.426	0.22	0.625	0.835	0.207	0.272	0.864	0.313

SNR = signal-to-noise ratio; PTF = phonation threshold flow; PTP = phonation threshold pressure; V_E = vocal efficiency; Amplitude R = amplitude of right vocal fold, Amplitude L = amplitude of left vocal fold, Interfold $\Delta\Phi$ = intravocal fold phase difference (right upper-left upper), Intrafold $\Delta\Phi$ = intervocal fold phase difference (right upper-right lower); VFP = vocal fold paralysis; ML = medialization laryngoplasty; hypo AA = hypoadducted arytenoid adduction; optimal AA = optimally adducted arytenoid adduction; hyper AA = hyperadducted arytenoid adduction.