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Effects of Arytenoid Adduction Suture Position on Voice Production and Quality

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Objectives/Hypothesis: Arytenoid adduction (AA) is performed to treat unilateral vocal fold paralysis with a large posterior glottal gap. However, the voice effects of AA suture position remain unclear. This study aimed to evaluate voice production and quality as a function of AA suture position on the thyroid ala in a neuromuscularly intact in vivo larynx.

Study Design: Animal model.

Methods: Unilateral recurrent laryngeal nerve and vagal paralysis were modeled in two canines. AA suture position was varied across five equidistant positions on the anterior inferior thyroid ala, from a paramedian position anteriorly to the oblique line posteriorly. Phonation was performed over 8×8 graded level combinations of recurrent and superior laryngeal nerve stimulation per suture position. The primary outcome was percent successful phonatory conditions. Secondary outcomes included fundamental frequency (F0), phonation onset pressure (PTP), cepstral peak prominence (CPP), and laryngeal posture.

Results: Anterior suture positions resulted in a greater percentage of successful phonatory conditions compared to posterior sutures. Suture position 2, located at the anterior inferior thyroid ala, resulted in the highest percentage of successful phonatory conditions, lowest PTP, and lower muscle activation levels to achieve higher CPP. Posterior sutures resulted in wider glottal gap and more effective F0 and vocal fold strain increase with cricothyroid muscle contraction, but with fewer successful phonatory conditions and higher PTP. Trends were consistent across both paralysis types.

Conclusions: AA suture placed in the anterior inferior thyroid ala resulted in the best acoustic, aerodynamic, and voice quality outcomes. This study provides scientific evidence for maintaining current clinical practice.

Key Words: Arytenoid adduction, phonosurgery, in vivo phonation, acoustics, aerodynamics, vocal fold paralysis.

Level of Evidence: NA

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INTRODUCTION

Dysphonia due to unilateral vocal fold paralysis (UVFP) is commonly treated with surgical medialization of the vocal fold. Options include injection augmentation, type 1 medialization thyroplasty (MT), and arytenoid adduction (AA). Current recommendations are to treat midmembranous glottal gaps with MT, and large posterior glottal gaps with AA alone or AA plus MT.[1] Most surgeons select AA to treat UVFP when 1) a large posterior glottal gap is present, 2) the paralyzed vocal process must be stabilized against the normal vocal process during phonatory adduction, or 3) a significant height mismatch exists between the vocal folds.[2]

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Isshiki et al. introduced the AA procedure. Using a posterior laryngeal approach, they followed the posterior cricoarytenoid muscle to the muscular process of the arytenoid cartilage, placed sutures on the muscular process, and pulled the sutures out through the anterior inferior region of the ipsilateral thyroid ala.[2] Their goal was to simulate the lateral thyroarytenoid (TA) and lateral cricoarytenoid (LCA) muscle vectors.[2] The TA vector is coplanar with the vocal fold, as the muscle courses from the anterior commissure area in the midsagittal plane of the thyroid cartilage to the anterolateral surface of the arytenoid. In comparison, the LCA vector is lateral and inferior, as the muscle courses from the superior surface of the lateral cricoid cartilage to the muscular process of the arytenoid cartilage.[3] Optimal AA suture placement remains unexplored. Isshiki et al. did not recommend an exact suture position on the thyroid ala, recognizing that the "optimal direction of pulling the muscle process remains to be studied further."[2]

Most surgeons follow the Isshiki method and perform suture placement in the general area of the anterior–inferior thyroid ala, whereas others use a more precise location.[1,4] AA is now commonly combined with MT,[5] which complicates AA suture placement because the medialization window and suture position overlap, and requires suture placement outside the MT window. In addition, a LCA muscle pull technique utilizing a more posterior suture position has been advocated.[6,7] Therefore, understanding the range of possible AA suture positions along the entire anterior–posterior dimension of the thyroid ala that do not compromise acoustic and aerodynamic outcomes is pertinent.

There are further reasons to investigate the effects of AA suture position. Suture position is a suspected cause of poor voice outcomes following AA.[8,9] The acoustic and aerodynamic effects of suture direction have been studied in cadaveric larynges but not in an in vivo model, where comprehensive assessment of muscular compensation is possible.[8,9] The normal vocal fold adductors and cricothyroid (CT) muscles can compensate in UVFP,[10] but their effectiveness at various AA suture positions is unknown. This study aims to evaluate how AA suture position on the thyroid ala affects voice production and quality using an in vivo model of UVFP. Our established in vivo model and graded neuromuscular activation of intrinsic laryngeal muscles (ILMs) allowed systematic variation of muscle activation to test AA suture position effects on physiologic phonatory postures and resultant acoustics, aerodynamics, and voice quality.

MATERIALS AND METHODS

In Vivo Canine Model of Phonation

The Institutional Animal Research Committee at the University of California, Los Angeles, approved this protocol. Two young male mongrel dogs were used. Surgical exposure of the larynx, recurrent laryngeal nerves (RLNs), and superior laryngeal nerves (SLNs) was as previously described.[11,12] Nerve branches to the posterior cricoarytenoid muscle, Galen's anastomosis, and internal branch of the SLN were divided bilaterally. Appropriately sized tripolar cuff electrodes (Ardiem Medical, Indiana, PA) were applied to the RLN and SLN(s) to stimulate the adductor and CT muscles, respectively.

To simulate all neuromuscular activation conditions possible in UVFP, RLNs and SLNs were stimulated in various combinations for each suture position. A subglottal tube attached to the upper trachea provided rostral airflow for phonation. The nerves were stimulated with 0.1-millisecond cathodic pulses at 100 Hz for 1,500 milliseconds, whereas airflow was ramped linearly from 300 to 1600 mL/s. A humidifier (HumiCare 200; Gruendler Medical, Freudenstadt, Germany) warmed the air at the glottal level to 37.5°C and 100% relative humidity.

Neuromuscular Conditions Tested

Left UVFP was modeled as previously described.[10]

Unilateral RLN paralysis. The left RLN was not stimulated to model left RLN paralysis. The right RLN stimulation levels included baseline zero stimulation and seven evenly spaced stimulation levels from threshold (level 1) to maximal activation (level 7). Each RLN level was combined with baseline and seven similarly graded SLN levels to test all possible SLN/RLN activation combinations. Thus, 64 unique right RLN and bilateral SLN stimulation combinations (neuromuscular activation states) were tested per adduction suture position.

Unilateral vagal paralysis. Left RLN and SLN were not stimulated to model left vagal paralysis. Right RLN and SLN were stimulated as above in the unilateral RLN paralysis model, resulting in 64 unique right RLN/SLN neuromuscular activation states per adduction suture position.

Thus, for each UVFP type, 320 unique muscle neuromuscular activation states were studied per animal (64 conditions/suture × five sutures). We monitored the larynx preparation visually during the experiment and confirmed appropriate muscle stimulation with postexperiment high-speed video (HSV) evaluation. Threshold and maximal activation levels were retested for each nerve at experiment conclusion and remained unchanged.

Arytenoid Adduction

Left AA was performed as described by Bielamowicz et al..[4] A 4–0 Prolene suture was passed through the muscular process. An angiocatheter needle was passed through the designated positions on the thyroid ala, advanced just lateral to the muscular process, and was used to bring out both suture ends through the thyroid ala. All AA sutures were brought out of the thyroid ala initially to avoid larynx manipulation after experimental setup. Suture position was varied in the axial plane. Suture 1 was placed anteriorly, 3 mm lateral to the laryngofissure line, and suture 5 was placed posteriorly at the oblique line. Remaining sutures 2, 3, and 4 were placed equidistant between sutures 1 and 5 approximately 4 mm apart (Fig. 1). Sutures were vertically positioned about halfway between level of the vocal fold (based on the position of the anterior commissure) and the inferior thyroid cartilage border. Prior to phonatory testing, each tested suture was tied down on the thyroid ala over a two-hole miniplate[4] by the senior author (D.K.C.), who performs AA routinely. Before testing each new suture position, the previously tested suture was cut and the vocal process was gently lateralized to neutral position prior to tying down the new suture. Weights were not used to provide tension to best mimic operative conditions, where AA is performed by visual assessment of vocal fold adduction and haptic feedback of appropriate suture tension.

Measurement of Experimental Parameters

For each neuromuscular activation condition, the following parameters were recorded: acoustics, aerodynamic pressure, and laryngeal posture. A probe tube microphone (Model 4128; Bruel & Kjaer North America, Norcross, GA) and pressure transducer (MKS Baratron 220D; MKS Instruments, Andover, MA) mounted flush with the inner wall of the subglottic tube measured acoustic

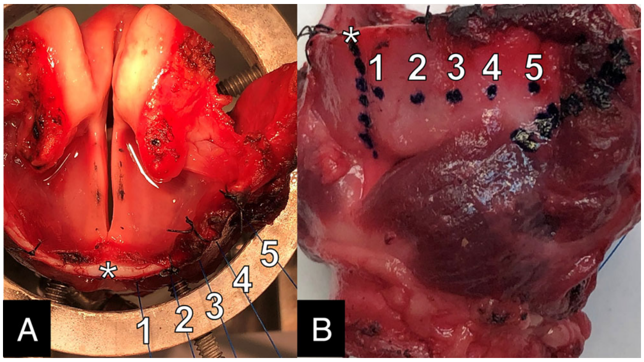

Fig. 1. Illustration of the five suture positions using an ex vivo canine larynx supraglottic laryngectomy preparation. Suture 1 is positioned 3 mm from the laryngofissure line anteriorly, and all sutures are positioned equidistantly apart by approximately 4 mm. In the vertical dimension, the sutures are positioned halfway between the anterior commissure (*) and the inferior border of the thyroid cartilage. (A) Superior view. (B) Oblique view.

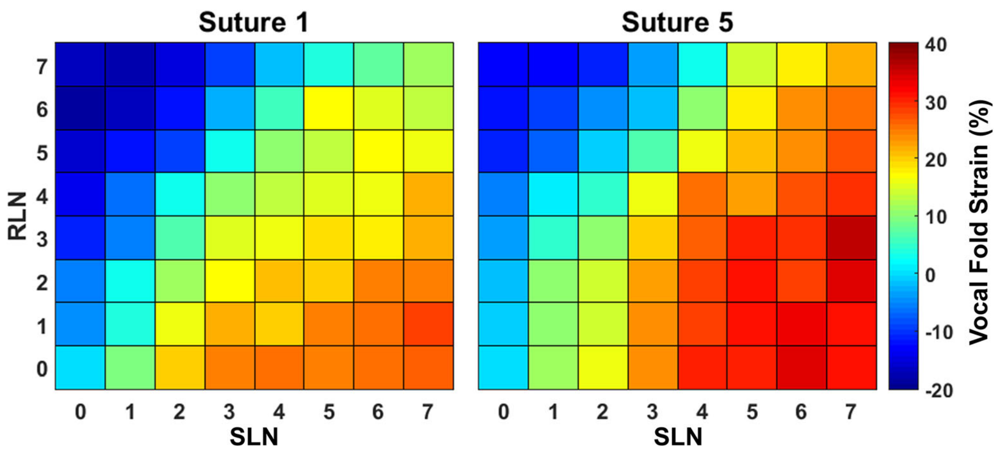

Fig. 2. Muscle activation plot of vocal fold strain in left recurrent laryngeal nerve (RLN) paralysis model over seven graded levels of right RLN and bilateral superior laryngeal nerve (SLN) stimulation, showing adduction suture positions 1 and 5. Increased strain was seen in suture 5 compared to 1.

and pressure signals. Fundamental frequency (F0) was manually determined at phonation onset using the first four cycles of the acoustic signal. Corresponding subglottal pressure was recorded as phonation threshold pressure (PTP). Cepstral peak prominence (CPP), quantifying voice quality, was determined from the first 0.5 seconds of stable phonation using Praat version 6.1.09.[13]

An HSV camera (Phantom v210; Vision Research, Wayne, NJ) imaged laryngeal posture and vibration at 3,000 frames/sec. Several India ink landmark positions on the superior vocal fold surface served as references for measurements. Glottal gap (distance between vocal processes [Dvp]) was measured as the distance in pixels between India ink landmarks over the vocal processes. Left vocal fold length was measured after adduction from the anterior commissure to the vocal process at baseline (L_0) and at midpoint of larynx stimulation (L_i). Strain was then calculated as the percent change from baseline: $\varepsilon = (L_i - L_0)/L_0$. Dvp was measured at the same midstimulation time point.

Data Presentation and Interpretation

Muscle activation plots (MAPs) were used to present results for ease of data interpretation. MAPs contain RLN activation levels (0–7) on the y-axis and SLN activation levels (0–7) on the x-axis. This 8 × 8 plot allows concurrent presentation of all 64 activation conditions per suture position. The color-coded format allows visual interpretation of data trends for a large number of related laryngeal activation conditions, as previously reported.[10–12] For consistency and ease of interpretation, comparative suture-position MAP data are presented in figures for RLN paralysis. Data trends were consistent across both RLN and vagal paralysis models, as elaborated in the results section.

Ethical considerations prevent utilization of multiple animals; thus, the minimum needed to test/retest experimental conditions and confirm data patterns are used. As such, voice production research, especially research relying on large animals, emphasizes data trends. Findings were generally consistent for both larynges and differences are noted. Our current findings are experimentally robust, consistent with previous studies, and reflect fine experimental control of laryngeal muscle activation and their phonatory consequences in an in vivo larynx.

Strain, Dvp, and CPP followed a normal distribution and were analyzed using matched-pairs two-tailed *t* tests. A matched-pair was defined by RLN and SLN activation levels. A pair was excluded from the *t* test for CPP if the pair was not complete (i.e., activation condition did not phonate). F0 did not fit a

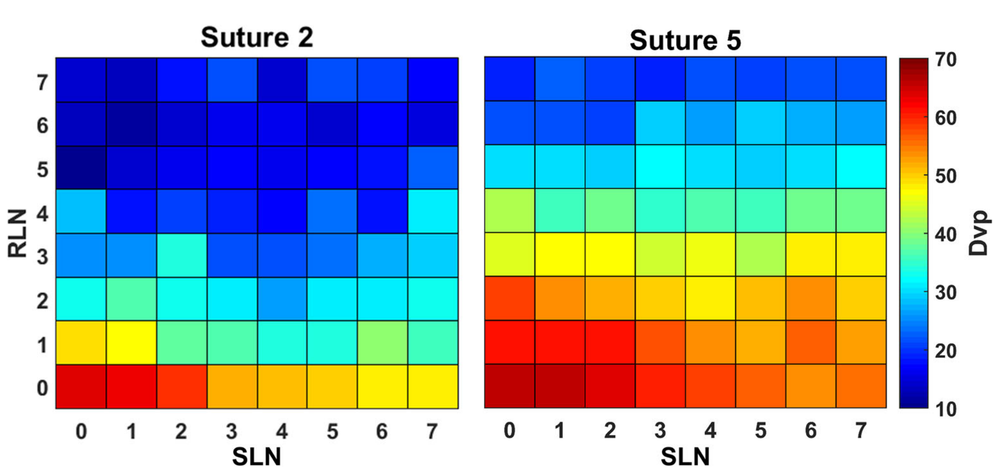

Fig. 3. Muscle activation plot of glottal gap in left recurrent laryngeal nerve (RLN) paralysis model over seven graded levels of right RLN and bilateral superior laryngeal nerve (SLN) stimulation, showing adduction suture positions 2 and 5. Greater glottal closure was seen in suture 2 compared to suture 5. Scale is in pixels. Dvp = distance between vocal processes.

TABLE I.
Percent Successful Phonatory Neuromuscular Conditions in Various Adduction Suture Positions.

Suture Position	Larynx 1 RLN, %	Larynx 1 Vagal, %	Larynx 2 RLN, %	Larynx 2 Vagal, %
1	78	78	92	83
2	84	84	91	69
3	47	47	86	77
4	56	50	75	59
5	59	50	73	66

Successful Phonatory Conditions. RLN = recurrent laryngeal nerve paralysis; Vagal = vagal nerve paralysis.

normal distribution; therefore, nonparametric measures are presented. Significance was defined as $P < .05$.

RESULTS

In each animal, 640 unique neuromuscular phonatory posture conditions were tested across two paralysis types, five suture positions, and eight activation levels each of the RLNs and SLNs. Resulting acoustic and aerodynamic data were analyzed for both larynges. Posture data were only available from the first larynx due to corrupted HSV data.

Effects on Laryngeal Posture

Vocal fold strain increased with SLN activation and decreased with RLN activation (Fig. 2). SLN (i.e., CT muscle) activation increased strain more effectively in RLN paralysis compared to vagal paralysis for a given suture position. In addition, SLN activation increased strain more effectively in posterior sutures compared to anterior sutures (Fig. 2). In RLN paralysis, sutures 2 to 5 had significantly increased mean strain with SLN stimulation compared to suture 1 ($P < .05$; mean strain 8.9%, 13.6%, 16.5%, 13.2%, and 14.6%, for sutures 1–5, respectively). In vagal paralysis, suture 3 and 5 had significantly increased mean strain with CT muscle activation than suture 2 ($P < .05$; mean strain 8.3%, 7.4%, 11.8%, 10.3%, and 12.5%, for sutures 1–5, respectively).

Glottal gap (Dvp) decreased with RLN activation. In both paralysis conditions, suture 2 showed significant decrease in Dvp compared to all other suture positions ($P < .05$; Fig. 3). In RLN paralysis, mean Dvp in pixels were 36.5, 27.8, 47.1, 37.9, and 41.2, for sutures 1–5, respectively. In vagal paralysis, suture 1 additionally showed significant decrease in Dvp ($P < .05$) compared to posterior suture (3–5) positions ($P < .05$, mean Dvp in pixels 34.7, 27.2, 47.3, 41.1, and 43.6, for sutures 1–5, respectively). For a given suture position, there were no significant differences in glottal gap between RLN and vagal paralysis conditions.

Effects on Acoustics

For each suture position, 64 unique neuromuscular conditions were tested and the percent of successful phonatory conditions were noted. A successful phonatory condition is a neuromuscular posture that resulted in phonation. The greatest number of successful phonatory conditions occurred with sutures 1 and 2 for larynx 1, and sutures 1 to 3 for larynx 2 (Table I). RLN paralysis had an equal or greater number of successful phonatory conditions as compared to vagal paralysis for a given suture position.

F0 increased with SLN activation and decreased with RLN activation. For a given suture position, RLN paralysis generally had greater F0 range than vagal paralysis. Greater F0 range was seen in the posterior (4 and 5) than the anterior sutures (1 and 2) in both paralysis types. Of the anterior sutures, suture 2 had higher median F0, and comparable or larger pitch variation (determined by interquartile range) than suture 1 in both paralysis types (Table II).

Effects on Voice Quality

Generally, both SLN and RLN activation resulted in higher CPP values. In most suture positions, concurrently high levels of both RLN and SLN activation resulted in higher CPP values. However, suture 2 was an exception. In suture 2, higher CPP values were achieved at lower

TABLE II.
Effects of Adduction Suture Position on F0.

Effects of Adduction Suture Position on F0 (Hz)

Suture	Larynx 1 RLN Median	Larynx 1 RLN Range	Larynx 1 RLN IQR	Larynx 1 Vagal Median	Larynx 1 Vagal Range	Larynx 1 Vagal IQR	Larynx 2 RLN Median	Larynx 2 RLN Range	Larynx 2 RLN IQR	Larynx 2 Vagal Median	Larynx 2 Vagal Range	Larynx 2 Vagal IQR
1	139	226	89	145	141	81	151	156	70	120	138	46
2	159	253	97	217	295	181	153	165	72	140	157	77
3	135	264	182	156	229	149	159	157	78	137	150	77
4	99	296	109	75	161	62	178	188	84	159	173	108
5	98	347	142	77	271	78	189	214	93	159	187	93

F0 = fundamental frequency; IQR = interquartile range; RLN = recurrent laryngeal nerve paralysis; Vagal = vagal nerve paralysis.

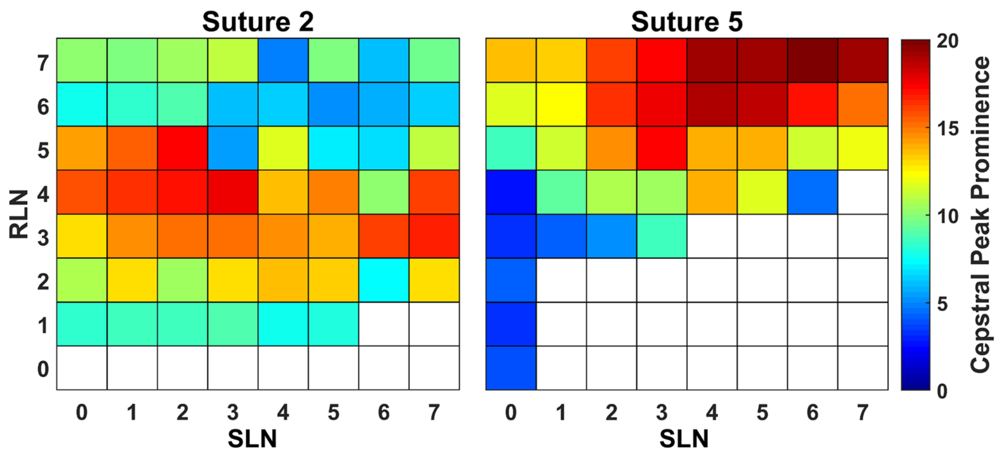

Fig. 4. Muscle activation plot of cepstral peak prominence (CPP) in left recurrent laryngeal nerve (RLN) paralysis model over seven graded levels of right RLN and bilateral superior laryngeal nerve (SLN) stimulation, showing adduction suture positions 2 and 5. Higher CPP values were reached at lower muscle activations levels in suture 2. White boxes represent neuromuscular conditions that did not phonate.

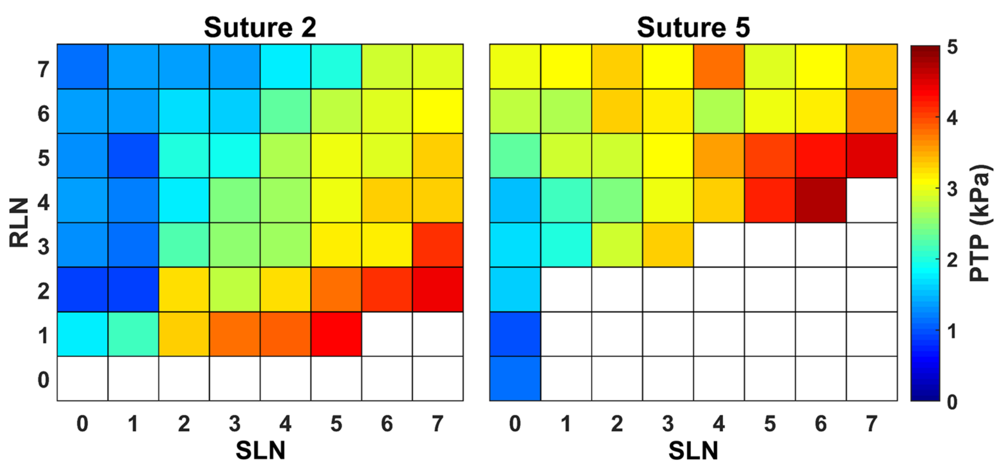

Fig. 5. Muscle activation plot of phonation threshold pressure (PTP) in left recurrent laryngeal nerve (RLN) paralysis model over seven graded levels of right RLN and bilateral superior laryngeal nerve (SLN) stimulation, showing adduction suture positions 2 and 5. Suture 2 resulted in lower PTP requirements than suture 5. This lowered PTP likely contributed to the increased number of successful phonatory conditions in suture 2. White boxes represent neuromuscular conditions that did not phonate.

RLN and SLN levels compared to higher RLN and SLN levels in other suture positions (Fig. 4). Interestingly, increasing RLN activation to the highest levels in suture 2 resulted in lower CPP values. This trend was consistent in both paralysis types.

Effects on Aerodynamics

PTP increased with SLN activation and decreased with RLN activation. Suture 2 required the lowest PTP compared to all other suture positions ($P < .05$) (Fig. 5). Suture 5 required the highest PTP compared to all other sutures ($P < .05$). Sutures 1, 3, and 4 resulted in statistically similar PTP requirements. For a given suture position, there were no significant differences in PTP between RLN versus vagal paralysis.

DISCUSSION

This is the first study to investigate the phonatory effects of AA suture position using a neurologically intact in vivo larynx. Systematic and graded stimulation of RLN and SLN allowed for study of all neuromuscular compensation conditions anticipated in UVFP. Our model further allowed for direct comparison between RLN and vagal paralysis conditions.

The ideal AA suture position could be defined in many ways. We first defined this as the sultinguture position facilitating the most phonatory conditions. This is a relevant measure because many phonatory conditions with various RLN/SLN combinations are possible in UVFP. Anterior suture positions facilitated a greater number of neuromuscular combinations to phonate successfully. Anterior sutures were noted to facilitate successful phonation (Table I) due to 1) decreased PTP requirement compared to posterior sutures (Fig. 5) and 2) improved glottal closure, which allowed phonation at lower RLN compensation levels (Fig. 3). In this regard, suture position 2 appears most optimal for AA. This position also facilitated improved vocal quality (CPP) at lower compensatory levels of the contralateral RLN (Fig. 4). Additionally, this position appears to best approximate the LCA vector, as suggested by recent magnetic resonance imaging studies of LCA orientation.[14] Therefore, it is reasonable to assume that suture 2 best simulated the effect of LCA muscle activation, resulting in improved glottal closure at the vocal processes and increasing the percentage of successful neuromuscular phonatory conditions.

In contrast to anterior sutures, posterior sutures allowed for more effective vocal fold strain increase with CT muscle activation (Fig. 2), generally resulting in greater F0 range (Table II). The cricoarytenoid joint is a saddle joint with a large anterior rocking motion range, from 37° to 63°.[15] Anteriorly directed sutures may increase the anterior arytenoid rocking motion, which in turn introduces vocal fold laxity and restricts the amount of elongation that can be achieved by CT activation. In contrast, the lateral vector of the posterior sutures may better stabilize the arytenoid and limit anterior rocking, facilitating more effective vocal fold lengthening with CT activation (Fig. 2). However, posterior sutures are suboptimal in two ways. First, posterior sutures close the glottal gap less effectively (Fig. 3) and thus require greater contralateral vocal fold compensation for glottal closure. Second, increased glottal gap and strain associated with posterior sutures require higher PTP for glottal vibration, resulting in fewer successful phonatory neuromuscular conditions (Fig. 5, Table I). AA sutures requiring lower PTP are less physically demanding and preferable.

We quantified voice quality using CPP values. CPP correlates well with dysphonia degree and duration,[16] even for severely aperiodic signals such as tracheoesophageal voice.[17] CPP quantifies the relative strength of the harmonic versus inharmonic components and does not require stable F0, unlike jitter, shimmer, and harmonics-to-noise ratio measures.[18,19] CPP is a replicable measure of voice quality than perceptual ratings due to the inherent biases and inconsistent ratings introduced by listeners.[20] Given these advantages and the large number of phonatory conditions in our study, CPP served as the preferred measure of voice quality than perceptual evaluation. At suture position 2, midlevels of RLN activation produced higher CPP values compared to low and high RLN levels (Fig. 4). This was consistent with the perceptually breathy voice quality at low RLN activation, and perceptually overadducted or strained voice quality at high RLN levels. Our determination of suture position 2 as optimal is consistent with the notion that in physiologically normal larynges, ideal voice occurs at midrange muscle activation levels, whereas perceptually breathy voice occurs at low RLN levels and strained voice at high RLN levels.[21]

The results of this investigation support current recommendations for AA suture position in the anterior–inferior thyroid cartilage. Although this finding maintains the status quo in clinical practice, we can now base the selection on scientific evidence. This study has several limitations. We did not apply standardized force to each adduction suture. However, Noordzij et al. found that the addition of further weight above 100 g in AA suture did not generate greater resistance to vocal process lateralization.[22] Thus, the suture can be tied using haptic feedback. The canine model introduces anatomical and physiological differences. However, systematic ILM activation cannot be ethically performed in an intact human larynx among others, and we have shown that the canine larynx most closely matches the human larynx in both anatomy and physiology.[11,12,23] We used an acute RLN injury model, which does not fully reflect possible reinnervation that occurs after vocal fold paralysis. In addition, our RLN stimulation model may activate all adductor muscles equally, which may not reflect individual control of adductor muscles possible in physiologic phonation. Finally, we did not investigate other scenarios that may be pertinent, such as AA suture position in the setting of MT or suture positions on the cricoid cartilage. These require further investigation.

CONCLUSION

In their seminal article introducing AA, Isshiki et al. noted that the effects of AA suture position required further investigation. We investigated ideal adduction suture position in an in vivo canine model using acoustic, aerodynamic, and voice quality outcomes. AA suture positioned in the anterior–inferior thyroid ala (approximately 7–8 mm posterior to the laryngofissure line and halfway between the vocal fold and inferior thyroid cartilage border level) was most ideal in both RLN and vagal paralysis models based on number of successful phonatory conditions, F0 range, PTP, vocal quality at medium muscle activation levels, and glottal closure.

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