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Phonatory Effects of Type I Thyroplasty Implant Shape and Depth of Medialization in Unilateral Vocal Fold Paralysis

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Abstract

Objectives/Hypothesis—Medialization thyroplasty (MT) is commonly used to treat glottic insufficiency. In this study, we investigated the phonatory effects of MT implant medialization depth and medial surface shape.

Methods—Recurrent laryngeal nerve (RLN) and vagal paralysis were simulated in an in vivo canine. A type 1 MT was performed using a silicone elastomer implant with variable medialization depths and medial surface shapes: rectangular, V-shaped, divergent, and convergent. The effects on phonation onset flow/pressure relationships and acoustics were measured.

Results—Increasing depth of medialization led to improvements in fundamental frequency (F0) range and normalization of the slope of pressure/flow relationship toward baseline activation conditions. The effects of implant medial shape also depended on depth of medialization. Outcome measures were similar among the implants at smaller medialization depths. With large medialization depths and vagal paralysis conditions, the divergent implant maintained pressure/flow relationship closer to baseline. The vagal paralysis conditions also demonstrated decreased fundamental frequency range and worse flow/pressure relationship compared to RLN paralysis.

Conclusions—The depth and medial shape of a medialization laryngoplasty (ML) implant significantly affect both the F0 range and aerodynamic power required for phonation. These effects become more notable with increasing depth of medialization. The study also illustrates that ML is less effective in vagal paralysis compared to RLN paralysis.

Keywords

Vocal fold paralysis; medialization thyroplasty; canine

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INTRODUCTION

Injury to the recurrent laryngeal nerve (RLN) or vagal nerve causing unilateral vocal fold paralysis (UVFP) is most commonly due to surgery of the head and neck, skull base, or thoracic cavity.[1] UVFP changes the symmetry of glottal phonatory parameters, such as body cover stiffness, glottal length, width, and medial shape, and results in altered vocal quality and phonatory effort.

Since Isshiki's introduction of the type 1 thyroplasty technique, medialization laryngoplasty (ML) has become the most commonly performed surgical intervention for UVFP.[2] However, multiple technical modifications and implants of varying shapes and sizes have been proposed.[3–6] Proper positioning in the paraglottic space is a known requirement and the limitations of thyroplasty implant in closing the posterior glottis have been discussed. However, the voice outcomes after ML continues to be inconsistent in the hands of many otolaryngologists, as evidenced by the wide variety of implants, techniques, and variability in reported outcomes and follow-up periods.[2,3]

There continues to be a search for ML optimization addressing implant material and technique. Implant materials ranging from silicone, titanium, Gore-Tex (W. L. Gore & Associates, Newark, DE), and even an adjustable balloon implant have been considered.[4–6] Czerwonka et al.[7] found that posterior medialization resulted in the best vocal quality. Noordzij et al.[8] found that increased depth of insertion led to increased medialization of primarily the midmembranous vocal fold. Devos et al.[9] developed an adjustable titanium implant to allow for intraoperative adjustments of medialization depth.

In the present study, we performed a comprehensive evaluation of implant medialization depth and medial shape on phonatory parameters. The glottic medial surface shape during phonation in the direction of airflow may be convergent (C), divergent (D), or rectangular (R). Laryngeal modeling studies found that the D glottis resulted in the lowest phonation threshold pressure (P_{th}), but physical models found that a R or near-R glottis had the lowest P_{th}; therefore, it may be more ideal for phonation.[10] Since these early studies, little has been accomplished in applying these findings on surgical rehabilitation of glottic insufficiency. This investigation was thus performed to study the following clinical questions: what are the effects of 1) implant medial shape, 2) medialization depth, and 3) RLN versus vagal paralysis on phonatory outcomes after ML? Results further the understanding of aerodynamic changes in UVFP and effects of ML.

MATERIALS AND METHODS

In Vivo Canine Model

This study was approved by the Institutional Animal Care and Use Committee. Two mongrel canines were used. The larynges and laryngeal nerves were surgically exposed, as described previously.[11] Standard thyroplasty windows were created in the left. The inferior border of the window was made very close to the inferior border of the thyroid cartilage because the vocal fold is in a slightly lower position in canines and the superior border of the window was nearly at the superior vocal fold level. Silicone implants (Silastic [Dow

Corning, Midland, MA] with Young's modulus 1386 kPa) were carved such that their anterior-to-posterior medial edge paralleled a midline-adducted vocal fold. The entire implant was placed in the paraglottic space, and no subglottic medialization was performed. An R implant was first created (Fig. 1A), and all other implants were then carved from this template. For example, to make a D implant, the superior medial edge was cut back 3 mm laterally (Fig. 1B). To make a V-shaped (V) implant, both the superior and inferior edges were beveled so that the maximal area of medialization was at the middle of the medial surface. To evaluate increased depth of medialization, "long" implants were carved that were 3 mm longer medially. Implants were seated properly and remained immobile in the windows during phonatory recordings. The superior view of the implants and the resulting effect on the vocal fold is shown in Figures 2 and 3.

Both RLN and superior laryngeal nerve (SLN) were stimulated at the same graded level over seven levels of stimulation, from threshold to maximal activation, as described previously (total of 64 distinct laryngeal neuromuscular activation conditions per stimulation run set, including zero stimulation). After baseline stimulation (normal), each stimulation set consisted of either RLN or vagal paralysis, standard or long implants, with each medial shape implant. To simulate RLN paralysis, the left RLN was not stimulated; and to simulate vagal paralysis, the left RLN/SLN were not stimulated. A subglottal tube to provide rostral airflow for phonation was attached to the trachea at ring 2–3 and connected to an airflow controller (MCS Series Mass Flow Controller, Alicat Scientific, Tucson, AZ). The airflow rate was increased linearly from 300 to 1,600 ml/second from stimulation onset to end of nerve stimulation (duration 1,500 ms). The airflow at the glottic level was 37.5°C and 100% humidified.

Data Presentation and Interpretation

Raw data recorded were subglottal acoustics, aerodynamics, and high-speed video (3,000 fps). Fundamental frequency (F0) was calculated at phonation onset by manually determining the beginning of sustained wave forms.[11] Once phonation onset was determined, the corresponding airflow and subglottal pressure (Psub) were obtained. Muscle activation plots (MAPs) were utilized to illustrate and generate a qualitative assessment of the results. The MAP contains the SLN activation levels (0–7) on the y-axis and RLN activation levels (0–7) on the x-axis. Thus, this 8 × 8 plot concurrently presents all 64 different SLN and RLN laryngeal activation conditions using color coding that allows for a visual interpretation of data. This format has been used previously in voice research where data trends from a large number of laryngeal activation conditions are presented.[11] Visual analysis was performed by both the first author (M.I.O.) and the senior author (D.K.C.), and the observations were compared.

Microsoft Excel (Microsoft Corporation, Redmond, WA) was used to generate descriptive statistics (Table 1). Scatter-plots and simple linear regression were used to analyze acoustic and aerodynamic data. The variance within the means for F0, Psub, and flow between the standard and long implants for each form of paralysis and implant trial were evaluated using analysis of variance to avoid multiple *t* test comparisons. Variation within the mean for baseline and no implant conditions were determined using unpaired, 2-tailed, *t* test, assuming unequal variance given the difference in number of data points present between conditions because some conditions had no phonation onset. Flow-pressure relationships at phonation onset for each implant type are illustrated by plotting the aerodynamic data from the 64 activation conditions per set per implant. Due to space and total number of figure limitations, only select illustrative implant conditions are presented.

RESULTS

Baseline (Normal) and Paralysis Conditions

Flow/pressure relationship at baseline showed a shallow linear regression line indicating small increases in flow with increasing Psub. In contrast, the regression line was more vertical for the paralysis conditions because airflow requirement was greater to reach phonation onset due to decreased laryngeal resistance (Figs. (4 and 5). In general, both the pressures and the flow for phonation onset were lower for larynx 1 (slightly under-medialized; see Fig. 2) compared with larynx 2 (slightly over-medialized; see Fig. 3). The aerodynamic relationship was significantly different for vagal paralysis compared to RLN ($P < 0.05$). In vagal paralysis, significantly more increased flow was required, as displayed by the more vertical regression lines. This trend was seen in both larynges. The phonation threshold power (Psub * Flow) was decreased in both the simulated RLN and vagal paralysis for all trials.

SLN stimulation was always required for F0 increase. RLN stimulation led to decrease in F0 and increase in Psub. With unilateral RLN paralysis, more activation conditions achieved a higher F0 than baseline, but the F0 range was contracted. With vagal paralysis the mean F0 is decreased compared to RLN paralysis ($P = 0.03$ larynx 1; $P = 0.01$ larynx 2), and range is further contracted. The mean F0 for both RLN and vagal paralysis was higher than the baseline condition.

Type 1 Thyroplasty Effects on Posture

The various implants medialized the vocal fold to increasing depths as follows: larynx 1 standard implants, larynx 1 long implants, larynx 2 standard implants, larynx 2 long implants (Figs. (2 and 3). The implant effect on glottal medial shape was evident in that the D implant led to greater “show” of the medial surface when visualized from the superior view. The R was closer to C and V was closer to D implant in this regard.

Larynx 1: RLN Paralysis

ML facilitated tje onset of phonation at a lower RLN activation level (level 1) compared to no implant condition (level 2). Among the standard implants, the V implant demonstrated smoothest F0 transition and greater F0 range ($P = 0.88$). The V-implant also led to phonation onset in more activation conditions. As the implant depth increased (long implants), glottal area decreased and phonation onset was reached at lower levels of RLN activation. Whereas SLN stimulation was still necessary to increase F0 in all implant conditions, long implants generally led to higher onset F0 than standard implants. With the long implants, the C-implant appeared most effective in this regard, followed by R, V, and then D implant ($P = 0.05$).

In general, the slope of the flow/pressure fit line for all implant conditions was improved compared to paralyzed condition. Figure 4 illustrates the finding for the C implant. As the depth of medialization increased, the flow/pressure relationship normalized but did not reach the baseline condition. Among the long implants, the C-implant displayed the most optimal flow/pressure relationship, but the differences between the slopes were minimal.

Larynx 1: Vagal Paralysis

The variation within the mean for F0 within the standard implants was similar ($P = 0.84$). As the implant depth increased, mean F0 and F0 range increased, similar to the RLN condition. Within the long set, the mean F0 and range was greatest for the D, followed by the R, V, and C, with significant variation within the mean among the implants ($P = .02$). The flow pressure relationship improved with ML and all implants, but it was not as favorable as baseline or ML in RLN paralysis conditions. The R implant (both standard and long) showed a nonlinear response similar to the paralysis condition (Fig. 4B). Among the long implants, the C implant had the least improvement in flow/pressure relationship. The phonation threshold power was similar to RLN paralysis conditions.

Larynx 2: RLN Paralysis

The F0 range increased with ML as in larynx 1. The greatest F0 range was found in the R and C implants among the standard implants—and in the R and D among the long implants. However, the variance between the means was not significant in either group ($P = 0.38$ and 0.08). As in larynx 1, the flow/pressure relationship was similar between the short implants, with V showing least improvement in slope. Among the long implants, the C implant had many activation conditions where phonation onset was not reached, whereas the D implant maintained the most favorable flow/pressure relationship (Fig. 5A). The flow requirements for long implants were very high, nearly the maximum flow administered (Fig. 5). Among these, the D implant demonstrated the lowest flow requirement with the most optimal flow/pressure relationship. The phonation threshold power was low in the nonimplant conditions, but rose to very high levels in both the RLN and vagal paralysis sets in the second larynx. This is a function of the greater depth of medialization and resultant stiffness, requiring very high volumetric flow to produce phonation in this larynx.

Larynx 2: Vagal Paralysis

The greatest F0 range was present in the R implant and the long C implant for the short and long sets respectively. Like the previous observations there was no statistical difference within the short implants ($P = 0.90$), but there was a significant difference within the long implants ($P < 0.01$). The flow pressure curves appear similar for the short implants; however, the same pattern emerged with regard to the long implants, with the D implant characterized by most favorable (Fig. 5).

DISCUSSION

Compared to the existing literature, this in vivo study allowed for assessment of multiple levels of SLN and RLN activation on the results of ML. This is a more typical compensatory scenario in patients; postoperatively, the patient will adjust SLN/RLN activation levels to achieve their desired vocal quality. Thus, the use of an in vivo canine model allowed for evaluation of the effects of thyroplasty in presence of intact RLN and SLN, which would not be possible in ex vivo or physical models.

Fundamental Frequency

It is well established that F0 range is dependent on SLN activation.[12] F0 range was greater in RLN paralysis compared to vagal paralysis, and mean F0 was increased in the paralysis conditions (greater in RLN paralysis compared with vagal). In observing the MAPs, this directly correlated with reduced strain and unopposed SLN action in that only unilateral RLN was functional. Clinically, this likely represents the “paralytic falsetto” described by Lundy.[13] However, many forms of compensation occur, which varies the resulting mean F0.[14] Increasing the depth of medialization leads to increase in F0 range. This is consistent with the notion that medialization thyroplasty leads to an increase in the stiffness of the vocal fold.[8] Long implants led to the most increases in F0 and F0 range.

The changes associated with the individual implants are likely due to changes in medial surface shape and tension. The stiffness of the vocal fold superior-medial surface is less than the inferior medial edge.[15] In addition, the vocal ligament and the conus elasticus reside in the lower medial edge and are likely more resistant to stiffness increase with a thyroplasty implant.[15] The effects of the various implants are likely due to the relative ability to change the overall stiffness of these subsites. For example, the convergent implant at less depth of medialization was more effective at achieving an improved F0 range and improved flow/pressure relationship; however, with increasing depth of medialization, it appeared to be less effective because it created undesirable stiffness of the superior medial surface, eventually eliminating the mucosal wave and phonation onset at the longest depths. However, the D implant was less effective initially (compared to the convergent) but was more effective as insertion depth increased. This is likely because a D implant may match the stiffness (or be resisted by the stiff medial vocal fold) of the inferior medial vocal fold but minimally affect the vibratory pliability at the superior medial glottis. The V and R implants would be expected to behave intermediate to the C and D implants, and they do.

Flow/Pressure Relationship

Zhang[16] proposed that without a “restraining mechanism” of the thyroarytenoid (TA) and cricothyroid (CT) muscles, the vocal folds are blown apart during phonation, which leads to breathy dysphonia. This is demonstrated in Figure 4, where higher flow rates are encountered for the same Psub with RLN paralysis (compared to baseline), while the flow requirement in vagal paralysis conditions is even higher. This likely reveals why vagal paralysis is more difficult to manage surgically; both TA and CT are paralyzed. With ML, the flow pressure relationship showed less improvement in the vagal paralysis conditions compared to RLN paralysis. In general, less phonation onset flow is considered favorable because humans are flow-limited by a finite lung vital capacity. In order to achieve adequate phonatory subglottal pressure, the glottal aperture must be decreased by vocal fold adduction, and the vocal folds should restrained by activation of CT and TA muscles. However, CT and TA activation also increases onset pressure due to increased stiffness.

Thus, an efficient laryngeal flow pressure relationship would demonstrate minimal flow increase with increasing subglottal pressure.

Implant Comparisons

No single implant emerged as the “best” in all conditions. Instead, the optimal implant depended upon the depth of medialization. The first larynx (Fig. 2) was medialized less than the second larynx (Fig. 3). In this larynx, the effects of medialization depth were better seen because the longer implants showed improved flow/pressure relationships and aerodynamic power. In the second larynx, the effects of over-medialization, overly increased stiffness, and the influence of implant medial shape were more apparent. The maximal medialization achieved with the longer implants was characterized by higher flow and subglottic pressure requirement. Within the long implants, the D implant required the least flow over all the laryngeal activation conditions, and thus the most optimal flow/pressure relationship; it closed the glottic gap while maintaining the most favorable glottic stiffness at the vibratory surface. This was particularly illustrated in the vagal paralysis condition, which represents the most extreme implant medialization condition and the worst aerodynamic relationship in the paralyzed condition.

CONCLUSION

This study demonstrates the influence of thyroplasty implant medialization depth and implant medial surface shape on phonatory parameters in UVFP. The D implant appears to improve glottic closure with the least deleterious effect on glottal stiffness over all medialization depths. Further study is required in this area, specifically with regard to measurement of vocal efficiency, sound quality, direct measurements of glottal medial shape, and role of implant material stiffness.

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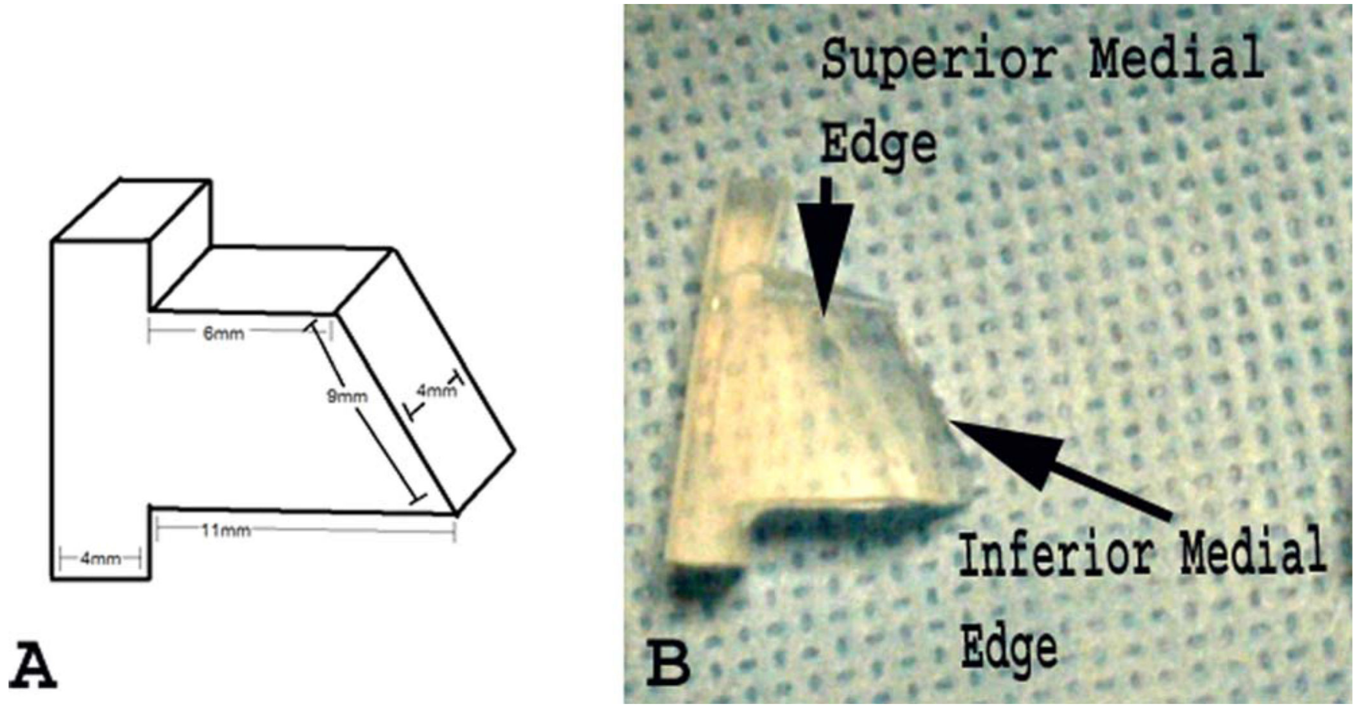

Fig. 1.
Implant shape and dimensions. (A) Diagram of implant template dimensions. (B) Photograph of a sample implant. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

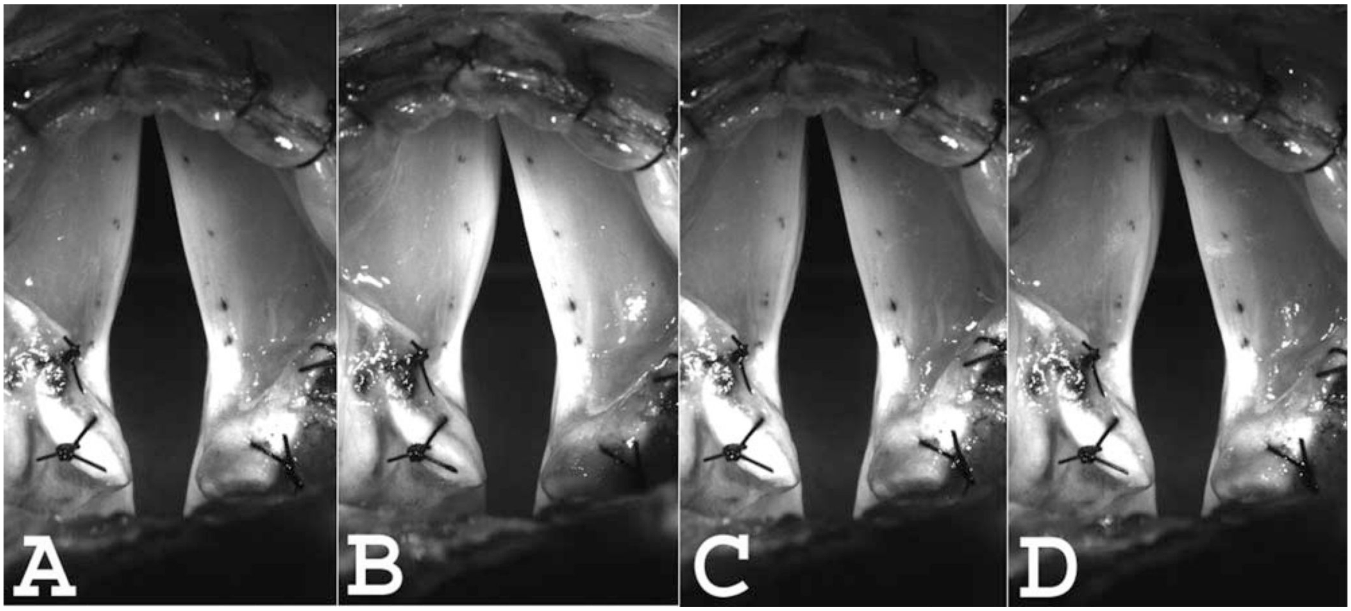

Fig. 2.

Images from high-speed video prior to neuromuscular stimulation illustrating the degree of medial displacement and shape of the vocal fold for select implant conditions from larynx 1. (A) Convergent. (B) Long convergent. (C) Divergent. (D) Long divergent.

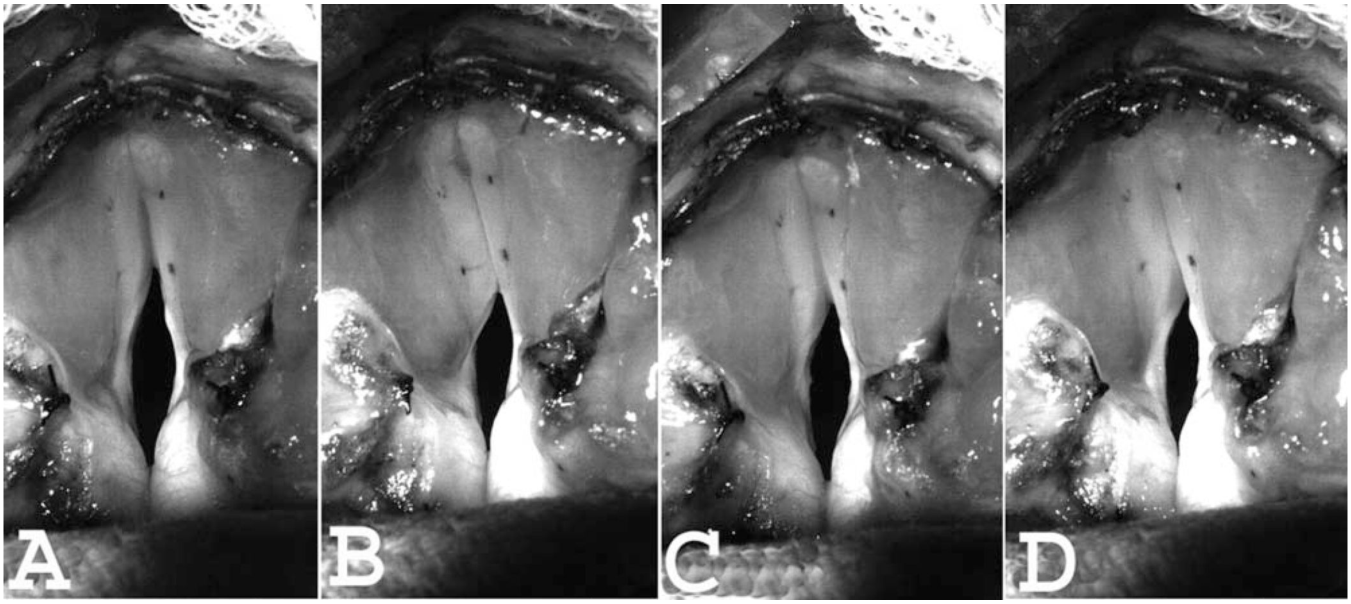

Fig. 3.

Images from high-speed video prior to neuromuscular stimulation illustrating the degree of medial displacement and shape of the vocal fold for select implant conditions for larynx 2. (A) Convergent. (B) Long convergent. (C) Divergent. (D) Long divergent.

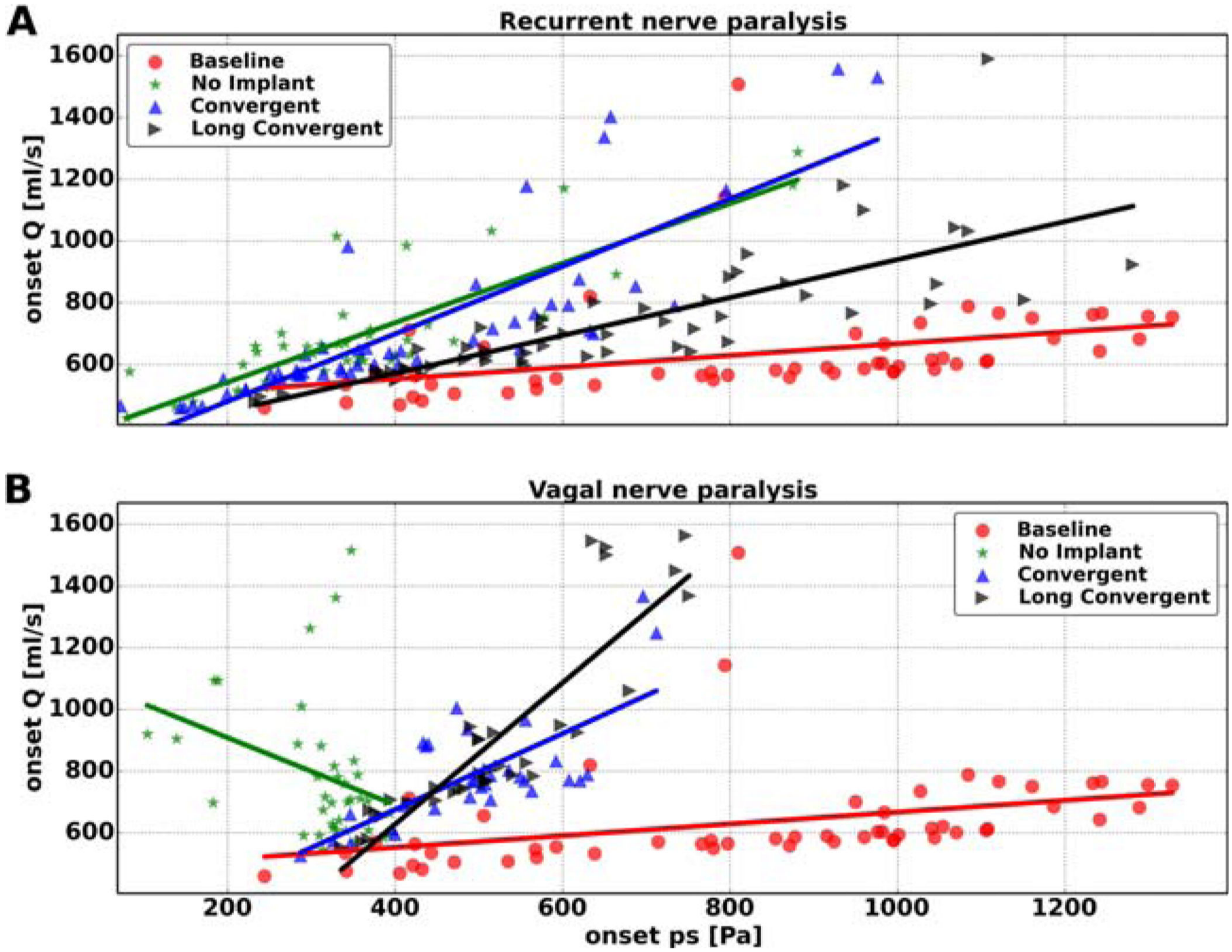

Fig. 4.

Scatterplot demonstrating select flow pressure relationship within larynx 1. Baseline and paralysis conditions represented, along with short and long implant comparisons. The x-axis represents threshold pressure (Psub) measured in Pa (pascal). The y-axis represents threshold flow measured in mL/sec. (A) Recurrent laryngeal nerve paralysis. (B) vagal paralysis. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

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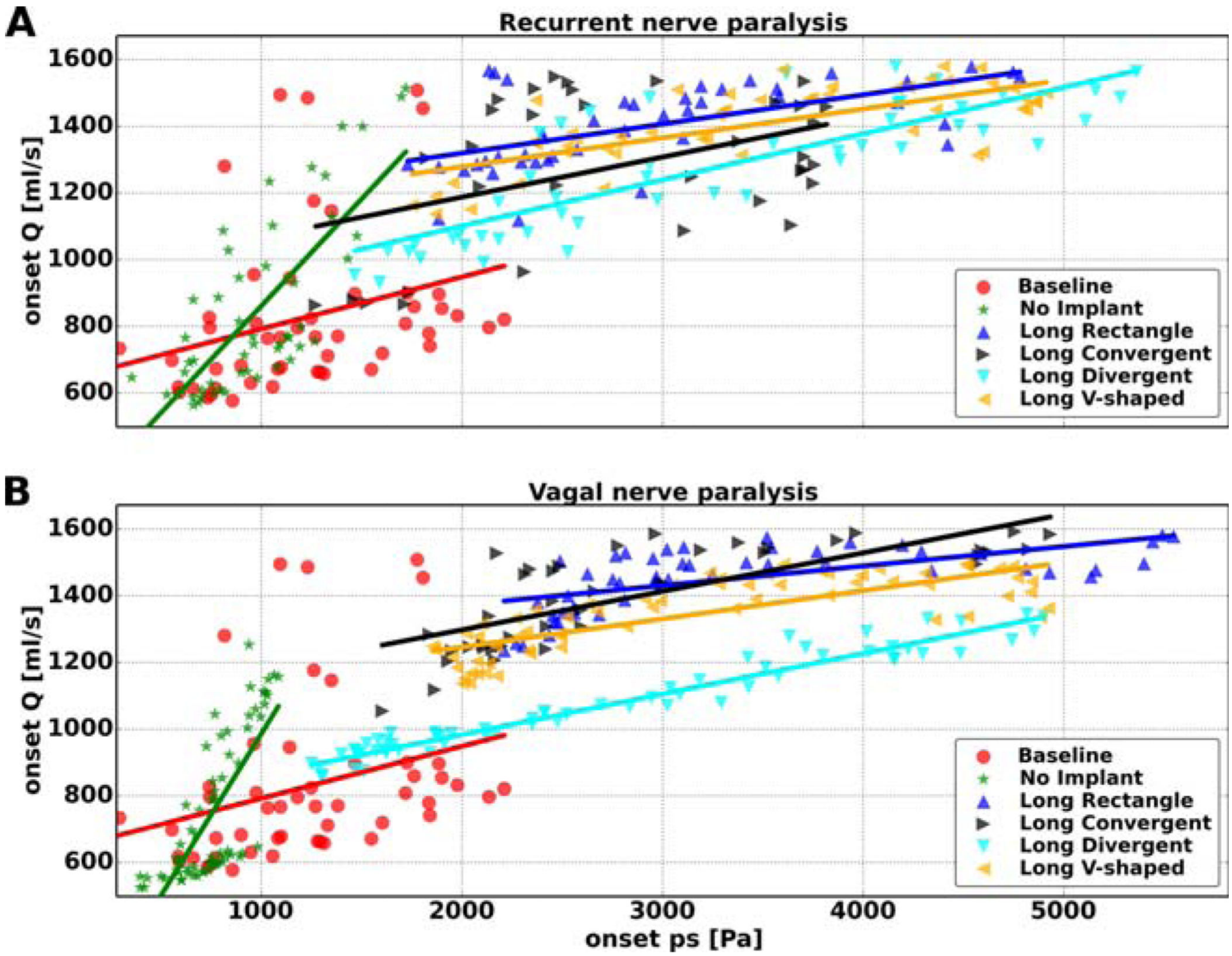

Fig. 5.

Scatterplot demonstrating select flow pressure relationship within larynx 2. Baseline and paralysis conditions represented along with long implants. The x-axis represents threshold pressure (Psub) measured in Pa (pascal). The y-axis represents threshold flow measured in mL/sec. (A) Recurrent laryngeal nerve paralysis. (B) Vagal paralysis. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

TABLE 1

Summary Statistics for each Implant Condition

Parameter (Average)	Baseline	No Implant	Convergent	Divergent	Rectangular	V shaped	Long C	Long D	Long R	Long V
Larynx 1, Simulated Recurrent Laryngeal Nerve Paralysis										
F0	129	170	163	155	156	149	192	147	175	197
F0 Range	271	201	212	225	231	282	355	206	288	270
Onset flow (ml/s)	635	690	715	692	670	685	728	661	648	614
Onset pressure (Pa)	831	353	415	405	692	549	655	443	459	381
Larynx 1, Simulated Vagal Nerve Paralysis										
F0	129	142	146	159	146	145	185	171	148	146
F0 Range	271	96	171	184	175	204	175	366	256	253
Onset flow (ml/s)	635	788	805	728	802	813	893	756	869	943
Onset pressure (Pa)	831	311	496	432	363	583	516	513	611	676
Larynx 2, Simulated Recurrent Laryngeal Nerve Paralysis										
F0	196	246	285	278	299	335	352	315	300	249
F0 Range	259	529	524	660	820	821	766	817	886	688
Onset flow (ml/s)	828	846	1032	1157	1026	1221	1281	1101	1372	1401
Onset pressure (Pa)	1232	976	1797	2436	1927	2021	2782	3186	3088	3504
Larynx 2, Simulated Vagal Nerve Paralysis										
F0	196	199	216	217	229	222	332	263	208	180
F0 Range	259	251	340	320	359	348	748	619	196	203
Onset flow (ml/s)	828	707	947	891	904	917	1263	1069	1400	1344
Onset pressure (Pa)	1232	768	1459	1570	1610	1597	3290	2704	3706	3155

Abbreviations: F0 = fundamental frequency; Pa = pascal.