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Combined type IIIB with bilateral type I thyroplasty for pitch lowering with maintenance of vocal fold tension

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Abstract

Objective—To evaluate type IIIB thyroplasty using the excised larynx bench apparatus and determine how altering vocal fold contour by performing bilateral medialization of the inferior vocal fold affects phonation. This procedure could be performed in patients for whom pitch lowering is desirable, such as female-to-male transsexuals or male patients with mutational falsetto in whom intensive voice therapy was insufficient.

Methods—Aerodynamic, acoustic, and high-speed videokymographic data were collected for nine larynges at three subglottal pressure inputs for each of three conditions: normal; type IIIB thyroplasty; and combined type IIIB with modified bilateral type I thyroplasty intended to create a more rectangular glottal configuration. Each larynx served as its own control.

Results—Phonation threshold flow ($p=0.005$), phonation threshold power ($p=0.031$), and airflow varied across conditions with highest values for type IIIB thyroplasty and lowest for the combined procedure. Fundamental frequency was significantly different ($p<0.001$), decreasing by approximately 100 Hz from control to type IIIB trials, and then by approximately 15 Hz from IIIB to combined procedure trials. Vibratory amplitudes and intrafold phase difference were highest for type IIIB trials.

Conclusions—Addition of bilateral inferior medialization to type IIIB thyroplasty provided some further decrease in frequency, but mostly served to increase tension, reduce airflow, and produce a vibratory pattern which more closely mirrored control trials. Exploration of this combined procedure in patients may be warranted if not completely satisfied with the results from type IIIB thyroplasty alone.

Keywords

type IIIB thyroplasty; type I thyroplasty; pitch lowering; mutational falsetto; transgender phonosurgery

Introduction

Fundamental frequency is the primary factor determining whether one's voice is perceived as male or female [1]. Accordingly, having a fundamental frequency outside the normal range of one's gender could have significant effects on quality of life. The majority of studies on phonosurgical pitch alteration have focused on pitch elevation [1-6], such as that which may be desirable for persons undergoing male-to-female transsexualism. Procedures such as cricothyroid approximation and the Wendler's glottoplasty have garnered significant clinical interest and successful outcomes have been reported [6-10]. Pitch-lowering procedures, though, have received far less attention.

There are two groups of patients who could potentially benefit from such procedures. The first is female-to-male transsexual patients. While less common than male-to-female transitions, female-to-male patients account for between 20-35% of all transsexual patients [11-15] and the percentage may be increasing [11]. Androgen therapy is typically beneficial for voice changes, but these changes may be delayed or inadequate [16]. Failure rates of hormonal therapy for satisfactory voice change may also be underestimated, with voice change not occurring as easily as traditionally thought [16-18]. In a study of sixteen female-to-male transsexual patients, Van Borsel et al. reported that five subjects hoped for a faster change, two expected a greater change than that which occurred, one subject expected both a greater and quicker change, and three described voice changes negatively; importantly, two of the sixteen subjects did not experience any voice change due to androgen therapy [18]. As voice is critical to gender identity and social interaction [19-20], a residually high fundamental frequency may adversely affect the quality of life in a group of patients who are already at risk for such problems.

In addition to female-to-male transsexual patients, male patients with mutational falsetto may also benefit. Intensive voice therapy and psychotherapy are the standard treatment and typically provide a good result [21]; however, in patients in whom cognitive-behavioral therapy is delayed, treatment may be unsuccessful [21-23]. In such patients, surgical intervention may be warranted. Remacle et al. reported on seven patients undergoing relaxation thyroplasty, also termed type IIIB thyroplasty, for pitch lowering and treatment of mutational falsetto [24]. Outcomes were favorable, with significant lowering of fundamental frequency and decreased Voice Handicap Index. Type IIIB thyroplasty [25] is a modified form of the type III thyroplasty for vocal fold shortening proposed by Isshiki [26]. In the original procedure, vertical strips of the thyroid cartilage are removed and the remaining segments attached, thereby effecting posterior displacement of the anterior commissure. In the modified procedure, two vertical paramedian incisions are made and the lateral boundaries are sutured together, thus providing anterior compression without the need to remove any segments of thyroid cartilage.

The results reported by Remacle et al. [24] are encouraging and warrant additional investigation and consideration of the procedure on other phonatory parameters, particularly aerodynamics which may be altered by the patient's new glottic configuration. Anterior compression could conceivably result in a lax vocal fold with potential for breathy voice production. Such potential effects would be undesirable in patients seeking to achieve a

more male voice, which is less breathy than the female voice [27]. Modification of vocal fold contour via bilateral medialization could increase vocal fold tension and decrease breathiness. During puberty, the male thyroarytenoid muscle undergoes inferomedial hypertrophy, creating a more rectangular glottis and inducing a register change which contributes to lowering of fundamental frequency [28]. This same effect could theoretically be created surgically, with inferomedial augmentation of the vocal fold contour. This was recently explored by Mau et al. using vocal fold injection. They observed changes in the aerodynamic parameters of phonation threshold pressure and phonation threshold flow, but did not report acoustic outcomes.

In this study, we explored the effects of type IIIB thyroplasty on a wide range of phonatory parameters using the excised larynx bench apparatus. Additionally, we evaluated the effects of adding vocal fold contour modification via bilateral medialization thyroplasty with small, specially designed Silastic implants. We hypothesized that this addition could decrease airflow without sacrificing the effects of type IIIB thyroplasty on fundamental frequency.

Materials and Methods

Larynges

Nine larynges were obtained postmortem from canines sacrificed for purposes unrelated to this study according to the protocol described by Jiang and Titze [29]. Larynges were inspected to ensure that there were no signs of trauma or disorders were present and then frozen in 0.9% saline.

Apparatus

Supraglottic structures were removed to allow for imaging of vocal fold vibration. The superoposterior aspects of the thyroid cartilage were removed to allow insertion of a three-pronged positioning device into the arytenoids. The larynx was mounted on the excised larynx bench apparatus (figure 1) as described by Jiang and Titze [29]. A metal hose clamp secured the trachea to a tube connected to a constant pressure source. Air was passed through two humidifiers in series (Fisher & Paykel Healthcare Inc., Laguna Hills, California) to humidify and warm the air. Airflow was controlled manually; airflow (model FMA-1601A, Omega Engineering Inc., Stamford, Connecticut) and pressure were measured using transducers (Series 3850A, Hans Rudolph, Inc., Kansas City, MO).

Acoustic signals were collected using a microphone (model RTA-M, dbx Professional Products, Sandy, Utah) at a 45° angle to the vocal folds, 10 cm from the glottis. A National Instruments data acquisition board (model AT-MIO-16; National Instruments, Austin, Texas) and customized LabVIEW 8.5 software (National Instruments) were used to record aerodynamic signals sampled at 100 Hz and acoustic signals sampled at 40,000 Hz. Vocal fold vibration was recorded for 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 frames per second. Experiments were conducted in a triple-walled, sound-attenuated room to stabilize humidity and reduce background noise.

Experimental methods

Three conditions were evaluated: control; type IIIB thyroplasty; and combined type IIIB thyroplasty with bilateral modified type I thyroplasty. Each larynx served as its own control and all conditions for an individual larynx were performed on a single day. Control trials were conducted, a type IIIB thyroplasty was performed and a second set of trials performed, and then bilateral type I thyroplasty was performed a third set of trials conducted. Modified type I thyroplasty was performed using symmetric, specially carved Silastic implants intended to augment the inferomedial aspect of the vocal folds (figure 2). Implants were smaller than would be required for medialization thyroplasty performed for unilateral paralysis. Additionally, the implants were angled so that the inferior aspect was more prominent than the superior aspect. Windows were created using an 11 blade with the superior boundary just below the superior edge of the vocal fold. The window was positioned posteriorly to avoid any undesired medialization at the modified anterior commissure (figure 2).

Five trials were performed for each larynx at three different subglottal pressure inputs for each of the three conditions. Thus, there were 9 conditions (3 pressure inputs * 3 conditions) and 45 trials (9 conditions * 5 trials per condition) per larynx. Three subglottal pressure inputs at 2 cmH₂O increments were used to evaluate fundamental frequency (F_0) over a range of pressures. The lowest pressure was approximately 2 cmH₂O above the phonation threshold pressure for that larynx. Input pressures for a given larynx were the same across conditions; however, pressure inputs were not the same across all larynges due to differences in phonation threshold pressure. All reported subglottal pressures reflect absolute pressures, not pressures above the phonation threshold.

Trials were conducted as a sequence of 5 seconds of phonation followed by 5 seconds of rest. As type IIIB thyroplasty alters F_0 by changing vocal fold length, no additional vocal fold elongation was performed. Arytenoid position remained constant across trials within each larynx. Larynges were hydrated with 0.9% saline solution to prevent dehydration.

Data analysis

Airflow and pressure at the phonation onset were recorded as the phonation threshold flow and phonation threshold pressure, respectively. Phonation threshold power is equal to the product of these values. Subglottal pressure was an independent variable controlled by the experimenter; however, airflow at that subglottal pressure input was considered a dependent variable of interest. Reported values of subglottal pressure and airflow are absolute and not relative to the phonation threshold values.

Measured acoustic parameters included fundamental frequency (F_0), signal-to-noise ratio, percent jitter, and percent shimmer. Acoustic signals were trimmed to produce three 1-second segments per trial using GoldWave 5.1.2600.0 software (GoldWave Inc., St. John's, Canada) and these segments were analyzed using TF32 software (Madison, WI).

Videokymographic analysis was performed as described by Krausert et al. [30]. Briefly, video recordings were analyzed using a customized MATLAB program (The MathWorks, Natick, MA). Amplitude and phase of each of the four vocal fold lips (right upper, right

lower, left upper, and left lower) were quantified. Interfold phase difference was determined to evaluate vibratory symmetry, where a phase difference of π radians represents perfectly symmetric vibration, and a phase difference of zero radians represents perfectly asymmetric vibration. Both right and left intrafold phase difference were also determined, primarily to evaluate if adding the bilateral inferior medialization affected the movement delay between the lower and upper vocal fold lips.

Statistical analysis

One-way repeated measures analysis of variance (ANOVA) was performed to determine if threshold aerodynamic parameters differed across conditions. For all other parameters, two-way ANOVA with pairwise comparisons using the Student-Newman-Keuls method was performed to determine if significant differences occurred across conditions of interest (control; type IIIB thyroplasty; combined IIIB with bilateral type I thyroplasty), controlling for subglottal pressure input. As threshold aerodynamic parameters are not dependent on the experimenter-controlled subglottal pressure input for a given trial, a one-way ANOVA is sufficient for those parameters. All other parameters are likely influenced by subglottal pressure and thus this factor must be controlled. Analysis was performed using SigmaPlot 11.0 software (Systat Software Inc., Chicago, IL). Overall tests were two-tailed with a significance level of $\alpha=0.05$.

Results

Summary data and results of statistical analysis are presented in table 1.

Aerodynamics

Phonation threshold flow ($p=0.005$) and power ($p=0.031$) were significantly different across conditions, with lowest values for the combined procedure. Phonation threshold pressure did not vary significantly. Airflow was significantly different across conditions ($p<0.001$), with highest values for IIIB thyroplasty and lowest for the combined procedure (figure 3).

Acoustics

F_0 was different across conditions ($p<0.001$) (figure 4). At the intermediate subglottal pressure, mean F_0 was 273 ± 95 for the control trials, 179 ± 54 for IIIB, and 162 ± 42 for the combined procedure. Though frequency decreased with vocal fold contour modification, the change was not significant ($p=0.238$). Perturbation parameters were slightly higher for the combined condition (percent jitter: $p=0.056$; percent shimmer: $p<0.001$), though remained fairly low, with mean percent jitter of 0.92 ± 0.56 and percent shimmer of 5.96 ± 2.94 at intermediate subglottal pressure. Signal-to-noise ratio differed across conditions ($p<0.001$), with highest values for control trials, intermediate values for IIIB thyroplasty, and lowest values for the combined procedure.

Videokymography

Vibratory patterns are shown in figures 5 and 6. Across conditions, open/closed quotient and maximum displacement in the axial plane appeared different. Additionally, intrafold phase difference for both the right ($p<0.001$) and left ($p<0.001$) were significantly different across

conditions. For both measurements, phase difference was lowest for the control trials, highest for IIIB trials, and intermediate for the combined procedure. Right upper lip vibratory amplitude ($p=0.034$) and left lower lip amplitude ($p=0.006$) were also significantly different across conditions.

Discussion

Few studies have been conducted on pitch lowering procedures. As female-to-male transsexual patients represent approximately 25% of all transsexual patients and voice outcomes are not always optimal [15, 18], it could be beneficial to evaluate current and new procedures in the controlled setting of an excised larynx experiment. Beyond causing a decrease in fundamental frequency, type IIIB thyroplasty also had prominent effects on aerodynamics and vibratory properties. The addition of vocal fold contour modification also had significant effects on multiple phonatory parameters, most notably airflow and threshold aerodynamic measurements.

Posteriorly displacing the anterior commissure altered the axial glottal configuration. This new configuration was associated with a decreased F_0 as well as increased airflow and open quotient as visualized on high-speed video recordings. The degree of decrease in F_0 was comparable to that reported previously [24]; however, both the initial and final F_0 were higher due to the use of canine larynges, which are smaller than human larynges. The relatively higher final F_0 (range of means across subglottal pressures: 164 – 186 Hz) does not adversely affect interpretation of results, as the change in frequency was of greater interest than the specific value. Interestingly, phonation threshold flow was not significantly different for IIIB trials compared to controls. Although performing the IIIB introduced a slight glottic gap which would increase phonation threshold flow, it also shortened the length of the glottis, which would decrease phonation threshold flow. This parameter was significantly lower for the combined procedure compared to IIIB trials. Airflow, too, was lower. This could potentially be desirable clinically to decrease breathiness which is more associated with a feminine voice [27]. To this end, the addition of bilateral implants was effective.

The effects of adding bilateral implants on F_0 were less consistent. Although a decrease of 10-17 Hz was observed overall, changes were inconsistent across larynges and not statistically significant ($p=0.238$). Thus, the method may have to be modified if performed specifically for the purpose of further pitch lowering. Biomechanically, inserting inferiorly positioned implants to change vocal fold contour has several impacts. First, mass is increased; this by itself would be expected to decrease F_0 . Second, tension is increased, which would be expected to increase F_0 . Lastly, creation of a more rectangular glottis could conceivably result in decreased F_0 via a register change [28]. Overall, F_0 was decreased but not significantly so. Even without a further decrease in F_0 , there could be beneficial effects due to increased tension. We observed a vibratory pattern more closely mirroring that of the control condition as well as decreased airflow compared to trials with only type IIIB thyroplasty. Interestingly, perturbation parameters were higher with the combined procedure. Values remained relatively low, but it would be preferable to avoid any mild degradation in voice quality in patients with a normal larynx. This finding could potentially

be due to the use of slightly asymmetric implants resulting in mild mass imbalance or adduction asymmetry. Efforts were made to ensure implants were of approximately equal size, but implant chirality prevented them from being made simultaneously (i.e., simply cutting one block of Silastic into two).

High-speed videokymography has not been used previously to evaluate type IIIB thyroplasty and the findings were of interest. Normal-appearing vibratory patterns were maintained for both experimental conditions; however, vibration for the combined procedure appeared to resemble the control condition more than type IIIB trials did (figures 5, 6). This could be due to the increased tension provided by bilateral medialization. Interestingly, upper and lower lip amplitude was greatest for type IIIB trials, though only significantly so for the right upper and left lower lips. Creation of a lax vocal fold by type IIIB thyroplasty is expected to result in higher mucosal wave amplitude, as the vocal fold lips are more easily displaced by the airstream. A greater intrafold phase difference was observed for this condition as well, presumably due to longer independent excursion of the lower lip prior to movement of the upper lip. Despite these quantitative differences, kymograms for all three conditions were fairly similar (figure 6). Of note, open quotient was longest for type IIIB trials, with the combined procedure exhibiting inter-cycle vocal fold contact time more characteristic of the control trials.

Bilateral modified type I thyroplasty was performed rather than bilateral injection laryngoplasty for several reasons. First, it was easier to precisely control vocal fold contour with a solid implant than a fluid injectate. With the implant secured, there was no potential for it to move within the larynx; this could not be ensured if performing injection. Second, a key factor favoring injection over framework surgery is the less invasive nature of the procedure. In this study, bilateral medialization was intended to augment type IIIB thyroplasty, not replace it. If the cartilaginous framework is already exposed, the invasiveness of thyroplasty is no longer a concern. Third, the procedure would be easier to reverse in a patient if a suboptimal result were obtained. If intraoperative voicing demonstrates a worsening rather than improvement of voice frequency and quality, the implants can easily be removed and only the type IIIB thyroplasty retained. If injection were suboptimal, patients would have to wait until the material was resorbed. Lastly, thyroplasty must only be done once while injection must be repeated. While these reasons are clinically relevant, it may still be beneficial to explore injection laryngoplasty as a means of providing minimally invasive pitch lowering, particularly for those patients in whom androgenic effects on voice may be delayed or require only minimal frequency adjustment.

Performing this study in excised larynges allowed for exploration of a new method of pitch lowering and measurement of a wide range of phonatory parameters; however, all excised larynx experiments are inherently limited. Relevant to this study, we cannot evaluate effects of concomitant voice therapy or subject voluntary control over voicing. Additionally, long-term stability and benefit cannot be evaluated.

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Figure 1.
Excised larynx bench apparatus.

Figure 2.

Left: Silastic implant used to augment inferomedial surface of vocal fold. Right: Implant positioned within larynx to modify vocal fold contour.

Figure 3.

Airflow across conditions for each of three subglottal pressure inputs (approximately 8, 10, and 12 cmH₂O, though precise values varied across larynges). Subglottal pressure values are absolute and not relative to phonation threshold pressure.

Figure 4.

Fundamental frequency across conditions for each of three subglottal pressure inputs (approximately 8, 10, and 12 cmH₂O, though precise values varied across larynges). Subglottal pressure values are absolute and not relative to phonation threshold pressure.

Figure 5.

Frame-by-frame depiction of vibratory patterns for control (A), type IIIB thyroplasty (B), and combined IIIB with bilateral type I thyroplasty (C) trials for one larynx.

Figure 6.

Kymograms across conditions for one larynx. A = control; B = type IIIB thyroplasty; C = combined IIIB with bilateral type I thyroplasty. The numbers following the letter indicate the subglottal pressure for that trial.

Summary data for each condition at each of the three subglottal pressure (P_s) inputs. Values for P_s are absolute and not relative to PTP. Only one value is presented for threshold aerodynamic parameters as they are not dependent on subglottal pressure input for a given trial. PTP = phonation threshold pressure (cmH₂O); PTF = phonation threshold flow (L/min); PTW = phonation threshold power (cmH₂O*L/min); F_0 = fundamental frequency (Hz); SNR = signal-to-noise ratio; RU = right upper lip; RL = right lower lip; LU = left upper lip; LL = left lower lip; U interfold Φ = upper interfold phase difference; L interfold Φ = lower interfold phase difference.

Table 1

	Control			IIB thyroplasty			IIB/bilateral type I thyroplasty		
P_s	8.05±0.38	9.98±0.31	12.07±0.10	8.00±0.13	10.08±0.13	12.38±0.18	8.30±0.08	10.19±0.29	12.12±0.24
<i>Aerodynamic</i>									
PTP		10.66±4.43			9.32±3.06			7.90±2.00	
PTF		11.47±4.62			10.62±5.33			5.59±1.53	
PTW		137.04±115.78			106.76±82.65			44.75±18.75	
Airflow	15.88±0.98	21.63±0.47	24.52±1.55	2474±1.30	31.78±1.12	38.97±1.28	7.26±0.80	11.16±1.28	14.82±0.99
<i>Acoustic</i>									
F_0	266±91	273±95	279±91	164±63	179±54	186±54	152±64	162±42	176±31
% jitter	0.63±0.21	0.62±0.33	0.59±0.20	0.93±0.67	0.60±0.34	0.54±0.30	1.16±0.66	0.92±0.56	0.82±0.41
% shimmer	5.12±3.57	3.50±1.39	3.57±1.45	5.34±2.58	3.62±1.47	3.07±1.16	7.68±3.93	5.96±2.94	5.55±2.59
SNR	19.76±3.01	19.21±3.51	18.16±3.36	15.39±2.88	16.81±1.99	17.21±2.16	14.13±3.90	14.93±3.45	15.15±3.02
<i>VKG</i>									
RU amplitude	9.32±3.90	10.57±4.44	11.54±4.66	13.70±5.77	16.55±6.18	17.97±6.27	11.92±6.06	13.82±6.49	15.84±5.59
RL amplitude	8.20±4.33	9.53±5.06	10.76±4.91	17.00±8.29	20.59±11.02	21.67±10.66	9.73±5.98	11.52±7.06	12.96±7.02
LU amplitude	10.76±4.51	12.72±5.67	13.02±5.89	1491±7.90	18.36±10.49	19.49±10.54	12.45±6.15	13.85±6.96	16.47±6.45
LL amplitude	9.57±4.54	10.96±5.14	11.14±5.24	18.16±8.26	20.96±8.08	20.90±7.62	11.93±6.43	13.22±6.68	15.26±6.93
U Interfold Φ	2.55±0.37	2.58±0.37	2.77±0.26	2.32±0.56	2.55±0.48	2.53±0.42	2.43±0.70	2.54±0.56	2.44±0.59
L Interfold Φ	2.50±0.39	2.66±0.37	2.76±0.27	2.42±0.50	2.51±0.38	2.51±0.23	2.04±0.75	2.20±0.66	2.18±0.81
R intrafold Φ	0.67±0.31	0.57±0.31	0.58±0.20	1.84±0.87	2.01±0.63	1.99±0.56	1.16±0.31	1.10±0.32	1.26±0.27
L intrafold Φ	0.44±0.22	0.48±0.27	0.49±0.23	1.99±0.48	1.95±0.69	2.02±0.38	0.76±0.27	0.71±0.30	0.84±0.31

Table 2

P-values resulting from statistical analysis for overall analysis of variance (ANOVA) and pairwise comparisons. “–” = test not performed; PTP = phonation threshold pressure; PTF = phonation threshold flow; PTW = phonation threshold power; F_0 = fundamental frequency; SNR = signal-to-noise ratio; RU = right upper lip; RL = right lower lip; LU = left upper lip; LL = left lower lip; U interfold Φ = upper interfold phase difference; L interfold Φ = lower interfold phase difference.

Parameter	ANOVA	Control vs. IIIB	Control vs. combined	IIIB vs. combined
<i>Aerodynamic</i>				
PTP	0.112	–	–	–
PTF	0.005*	0.007*	0.617	0.008*
PTW	0.031*	<0.05*	>0.05	<0.05*
Airflow	<0.001	0.054	0.011*	<0.001*
<i>Acoustic</i>				
F_0	<0.001	<0.001*	<0.001*	0.238
% jitter	0.056	–	–	–
% shimmer	<0.001	0.746	<0.001*	<0.001*
SNR	<0.001	0.023*	<0.001*	0.030*
<i>VKG</i>				
RU amplitude	0.034	<0.05*	0.090	0.357
RL amplitude	0.902	–	–	–
LU amplitude	0.192	–	–	–
LL amplitude	0.006	0.005*	0.171	0.054
U Interfold Φ	0.786	–	–	–
L Interfold Φ	0.087	–	–	–
R intrafold Φ	<0.001	<0.001*	<0.001*	<0.001*
L intrafold Φ	<0.001	<0.001*	0.019*	<0.001*