The Laryngoscope

Dynamics of Phonatory Posturing at Phonation Onset

Travis L. Shiba, MD; Dinesh K. Chhetri, MD

Introduction: In speech and singing, the intrinsic laryngeal muscles set the prephonatory posture prior to the onset of phonation. The timing and shape of the prephonatory glottal posture can directly affect the resulting phonation type. We investigated the dynamics of human laryngeal phonatory posturing.

Methods: Onset of vocal fold adduction to phonation was observed in 27 normal subjects using high-speed video recording. Subjects were asked to utter a variety of phonation types (modal, breathy, pressed, /i/ following sniff). Digital videokymography with concurrent acoustic signal was analyzed to assess the timing of the following: onset of adduction to final phonatory posture (FPT), phonation onset time (POT), and phonatory posture time (PPT). Final phonatory posture time was determined as the moment at which the laryngeal configuration used in phonation was first achieved.

Results: Thirty-three audiovisual recordings met inclusion criteria. Average FPT, PPT, and POT were as follows: 303, 106, and 409 ms for modal; 430, 104, and 534 ms for breathy; 483, 213, and 696 ms for pressed; and 278, 98, and 376 ms for sniff-/i/. The following posturing features were observed: 1) pressed phonation: increased speed of closure just prior to final posture, complete glottal closure, and increased supraglottic hyperactivity; and 2) breathy phonation: decreased speed of closure prior to final posture, increased posterior glottal gap, and increased midmembranous gap.

Conclusions: Phonation onset latency was shortest for modal and longest for pressed voice. These findings are likely explained by glottal resistance and subglottal pressure requirements.

Key Words: Speech production, phonation onset, digital video kymogram, laryngeal posture.

Level of Evidence: NA.

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INTRODUCTION

The human larynx must reliably execute multiple tasks, including airway maintenance for respiration, airway protection during swallowing, execution of the cough reflex to clear the airway of secretions and foreign particles, and phonation for speech and other forms of communication. All of these complex functions are dependent on coordinated contraction of the intrinsic laryngeal muscles (ILMs) and are often dysfunctional in disease states such as neurodegenerative diseases (e.g., Parkinson's), laryngeal hypofunction (e.g., vocal fold paralysis), and hyperfunction (e.g., spasmodic dysphonia).[1–6] Thus, investigations of the dynamics of laryngeal posturing further our understanding of all laryngeal functions.

Laryngeal posturing for voice production begins with neuromuscular activation that sets the prephonatory posture (glottal adduction, length, width, stiffness, and tension),[6,7] followed by the attack phase (rise in subglottal pressure and onset of vocal fold oscillation that is perceived as sound).[7] The speed of vocal fold adduction is an important variable in the etiology of some voice disorders.[8] Dysfunction in the coordination of final phonatory posturing and phonation onset have been connected to impaired vocal efficiency and quality[9,10] and may be an indicator of neural dysfunction.[11,12] Proper glottal adduction and phonatory posturing are critical to achieve the desired pitch, intensity, and efficiency of phonation.[13,14]

The interactions of glottal posturing and aerodynamic energy from the lungs during voice production are highly coordinated events. It is generally thought that the vocal folds start rapid adduction about 50 to 100 ms before the expiratory airflow reaches them and that the prephonatory posture is set before audible voice is generated.[15,16] Mean phonation onset latency time (POT), defined as the time from onset of glottal adduction to production of the acoustic signal, was reported by De Biase et al. as 203 ms (standard deviation [SD] 72 ms),[17] and Hillel as 309 ms (SD 59 ms).[6] Both of these studies used laryngeal electromyography (LEMG) to record glottal adduction onset, combined with acoustic analysis to calculate POT. The events and postures occurring during this adduction period in modal and pathologic phonation remain of great interest.

The present study evaluates the dynamics of laryngeal posturing at phonation onset during the utterance of a variety of phonation types in normal human subjects. Using ultrahigh-speed video endoscopy, we examined glottal closure patterns and, using concurrently

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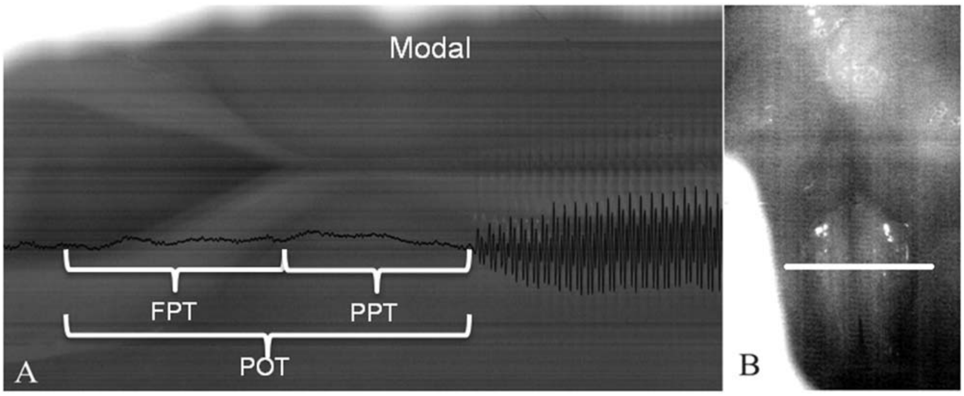


Fig. 1. Phonation kymograms and final phonatory posture: modal. (A) Digital videokymogram of closure pattern and (B) final phonatory posture for modal phonation. Concurrent acoustic signal is overlaid (black line) with the kymogram; FPT, PPT, and POT are marked with brackets. FPT = final phonatory posture time; POT= phonation onset time measurements; PPT= phonatory posture time.

recorded acoustic signal, determined the timing of glottal closure from onset of adduction to voice production. The results reveal variations in prephonatory adjustments depending on phonation type, contributing new information on laryngeal physiology that may also assist in furthering the evaluation and understanding of speech disorders of vocal onset.

MATERIALS AND METHODS

Subjects and Recording Procedures

This study was approved by the institutional review board. Twenty-seven phonetically knowledgeable untrained subjects with perceptually normal voices were directed to repeatedly utter the vowel /i/ in a variety of onset vocal qualities (modal, breathy, pressed) at comfortable loudness and duration. An expert with a background in linguistics demonstrated each phonation type to the subjects. A high-speed video camera (Phantom v210; Vision Research Inc., Wayne, NJ) recorded laryngeal dynamics during each utterance at 10,000 or 20,000 frames per second with a resolution of 480 $\times$ 360 or 360 $\times$ 240 pixels per frame. The larynx was visualized transorally using a KayPentax (Lincoln Park, NJ) 70-degree rigid laryngoscope and a 300-watt halogen light source. The acoustic signal was concurrently recorded using a hi-fidelity microphone at 50 kHz and synchronized with the video recording using the same reference clock for 6-second intervals.

Of the 243 phonation samples, 48 were excluded due to poor audio quality. The remaining 195 samples were rated for accuracy of phonatory type by two otolaryngologists, and 65 were eliminated because both raters did not agree that the targeted phonation type was achieved. This rating was done blind to the intent of the subject by deidentifying samples. Interrater reliability scores were calculated. The video quality of the remaining 130 samples was reviewed, and a majority were excluded due to 1) excessive anterior–posterior motion of the larynx during phonation, precluding accurate assessment of medial vocal fold movement by digital videokymogram (DVK); 2) phonation not starting with a fully abducted vocal fold; or 3) the inability to see the entire movement of the vocal processes from onset of adduction to phonation. Subject breakdown of the final 33 samples included for this study were as follows: breathy (N = 13) from 10 unique subjects; modal (N = 9) from eight unique subjects; and pressed (N = 11) from nine unique subjects.

Because the level of breathiness can vary, the breathy samples were further rated by two otolaryngologists and a speech pathologist using the rank and sort method[18] at a single sitting on a breathiness scale: 0 = not breathy (N = 3); 1 = mildly breathy (N = 4); 2 = moderately breathy (N = 7); and 3 = severely breathy (N = 2). There was 88% exact concordance among the raters between the ratings of the breathy samples. In two instances, the discrepancies were within 1 point on the scale and involved ratings of mildly breathy versus moderately breathy. Ratings for these two were determined by forced consensus among the raters.

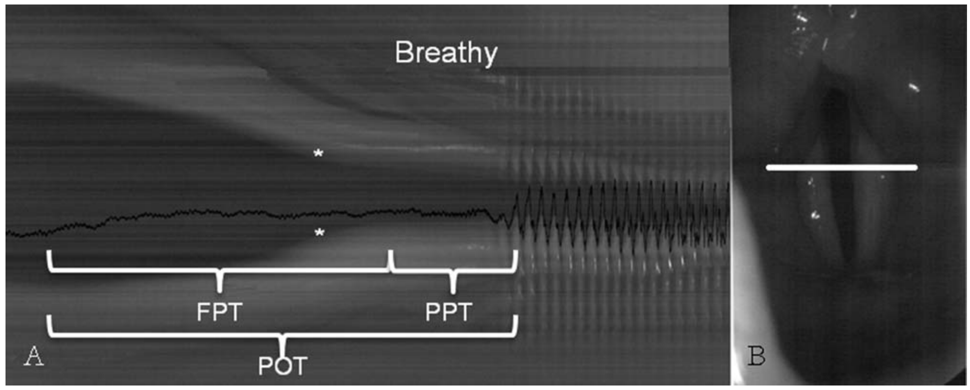
We also analyzed dynamics of 24 samples of /i/ phonation that followed a sniffing maneuver because this represents another type of posturing for phonation onset. For this task, the subjects were instructed to inhale sharply through the nose and then phonate /i/ while laryngeal posturing was visualized and recorded with a transoral laryngoscope.[19]

Measurements of Phonatory Posture Dynamics

Frame-by-frame analysis of video was performed using the Phantom Camera Control Application software (PCC 1.3; Vision Research Inc., Wayne, NJ) and by making a DVK with the kymogram line at the level of the vocal processes. Use of the DVK to follow movement of the vocal fold medial edge facilitated easy temporal localization of the video frame at the onset and offset of adduction as well as overall vocal fold closure pattern (Figs. 1–3). The video frame number at the onset of glottal adduction at the vocal process (first hint of glottal closure), end of glottal adduction (final phonatory posture), and phonation onset (vocal fold vibration with acoustic output) were recorded. Observations were made for presence or absence of supraglottal hyperactivity (SGH), midmembranous glottal gap (MMG), and posterior glottal gap (PGG). Vocal fold closure patterns were noted as follows: accelerations (transition to an increased slope of vocal fold closure, as noted in DVK), decelerations (transition to a decreased slope of closure, as noted in the DVK), and hesitations (plateaus or reversals of the slope of closure, as noted in the DVK).

The timing of the following phonatory postures were measured: final phonatory posture time (FPT) = the time to reach final phonatory posture from onset of adduction; phonatory posture time (PPT) = time from FPT to phonation onset; and phonation onset time (POT) = time from onset of adduction to phonation onset. Final phonatory posture time was determined as the moment at which the laryngeal configuration used in phonation was first achieved, which was typically the end of glottal medial movement for breathy phonation, or vocal process contact for the other phonatory types. Posturing mean duration and variances were compared with a Student t test between each group, with $P < 0.05$ considered significant.

Fig. 2. Phonation kymograms and final phonatory posture: breathy. (A) Digital videokymogram of closure pattern and (B) final phonatory posture for breathy phonation. Concurrent acoustic signal is overlaid (black line) with the kymogram; FPT, PPT, and POT are marked with brackets. *Single inflection point marking transition from fast closure to slow closure speed. FPT = final phonatory posture time; POT= phonation onset time measurements; PPT= phonatory posture time.



Acoustic Analysis

The fundamental frequency (F0) for each phonatory sample was assessed using Praat software.[20] The accuracy was also manually confirmed using Sound Forge (Sonic Foundry Sound Forge Version 6.0, Sonic Foundry, Inc., Madison WI) to measure the average F0 over four glottal cycles. From phonation onset, F0 varied for a short period until it stabilized (determined as 8 continuous glottic cycles with calculated F0 within 10%). Thus, the time to F0 stabilization (frequency stabilization time [FST]) was also noted. Comparisons of means and variances were made with a Student t test or Pearson's correlation calculation, significance at $P < 0.05$.

RESULTS

Phonatory Type Rating and Targeting

Overall interrater reliability for the blinded phonatory rating was 82% (159 of 195), and overall concordance of both raters with the attempted target phonation was 67% (130 of 195). Dual concordance (both raters agreed) for breathy voice was 74% (50 of 68), for modal voice was 79% (53 of 67), and for pressed voice was 45% (27 of 60). As mentioned in the methods section, the final 33 samples analyzed for this study required dual concordance for targeted phonation.

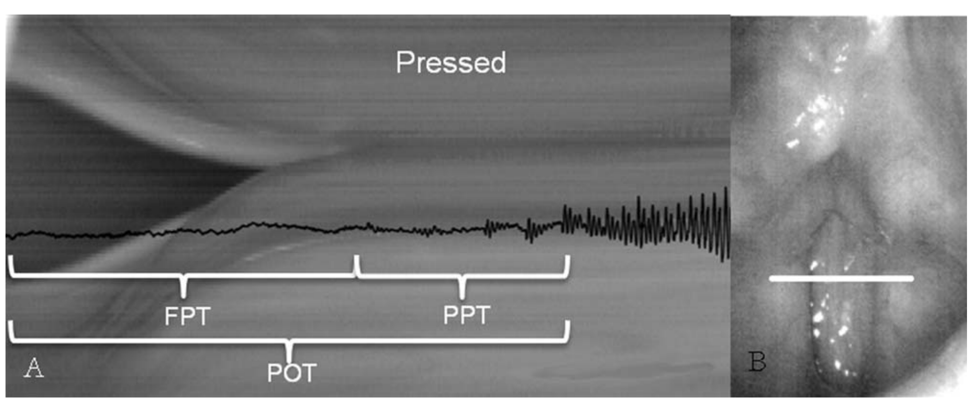
Posture Characteristics at Phonation Onset

Representative DVKs of phonation onset for modal, breathy, and pressed are shown in Figure 1A through 3A. Final phonatory posture images, shown in Figure 1B through 3B, represent the laryngeal configuration used just prior to phonation (i.e., prephonatory posture) for each phonation type. The observed incidences of closure patterns and final phonatory posture characteristics are illustrated in Figure 4. In modal phonation, one of nine (11%) samples demonstrated more than one inflection point (change in closure speed) during adduction; four of nine (44%) demonstrated change to a slower rate of closure immediately preceding final phonatory posture; two of nine (22%) PGG, four of nine (44%) MMG; and one of nine (11%) SGH. In breathy phonation, four of 13 (31%) demonstrated more than one inflection point; 13 of 13 (100%) demonstrated slowed rate of closure immediately preceding final phonatory posture; 13 of 13 (100%) PGG; 13 of 13 (100%) MMG; and 0 of 13 (0%) SGH. In pressed phonation, no samples demonstrated inflection points, a change to a slower rate of closure, or PGG. However, MMG was present in three of 11 (28%) and SGH in seven of 11 (64%). In sniff-/i/ phonation, no samples demonstrated more than one inflection point, and three of 24 (12.5%) demonstrated a change to a slower rate of closure immediately preceding final posture.

Posturing Dynamics

Posturing and phonation onset times by phonation types are shown in Figure 5. Average FPT, PPT, and POT were as follows: 278, 98, and 376 ms for sniff-/i/; 303, 106, and 409 ms for modal; 430, 104, and 534 ms for breathy; and 483, 213, and 696 ms for pressed. Detailed descriptive statistics and comparisons are provided in Table I.

Fig. 3. Phonation kymograms and final phonatory posture: pressed. (A) Digital videokymogram of closure pattern and (B) final phonatory posture for pressed phonation. Concurrent acoustic signal is overlaid (black line) with the kymogram; FPT, PPT, and POT measurements are marked with brackets. In this phonation type, FPT is bracketed distal to the area of complete glottal closure because there was continued glottal posturing activity beyond closure. FPT = final phonatory posture time; POT = phonation onset time; PPT= phonatory posture time.



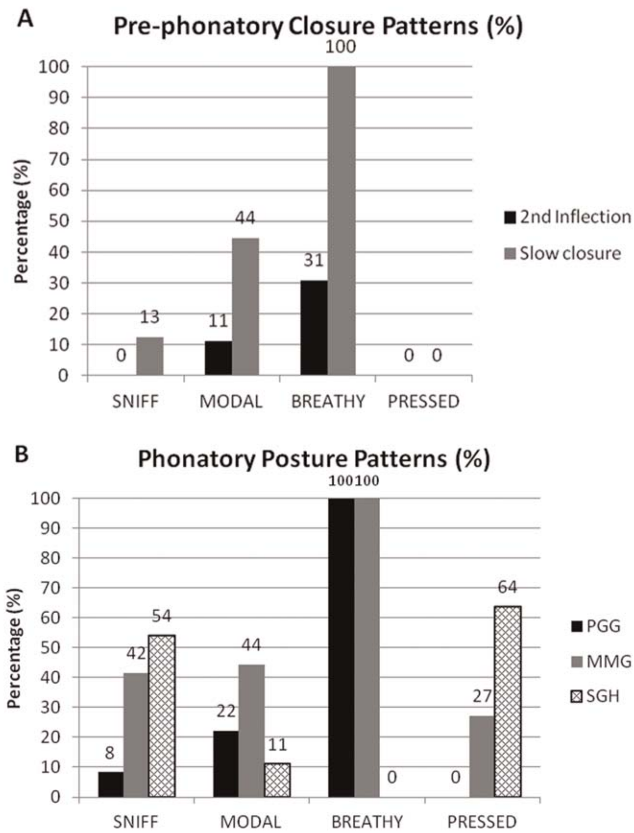


Fig. 4. Closure patterns and phonatory posture by phonation type. (A) Prephonatory closure (B) and final posture for various phonation types. Slow closure is defined as presence of flatter closing slope following a steeper closing slope on kymography just prior to final phonatory posture. Inflection points are transitions between closing phenotypes. Second inflection points, also called hesitations, were most common in breathy phonation.
PGG = posterior glottic gap at final phonatory posture; MMG = midmembranous gap at final phonatory posture; SGH = supraglottic hyperactivity at final phonatory posture.

Acoustic Features

Frequency stabilization times were 55 ms for the sniff-/i/ phonation, 59 ms for pressed, 92 ms for modal, and 183 ms for breathy. Frequency stabilization time was significantly longer for breathy than for sniff ($P <$ 0.000001), pressed ($P < 0.0001$), or modal (P =.035). No significant differences in FST were noted between sniff and pressed ($P = 0.34$). A higher breathy index rating was positively correlated with FST (Fig. 6).

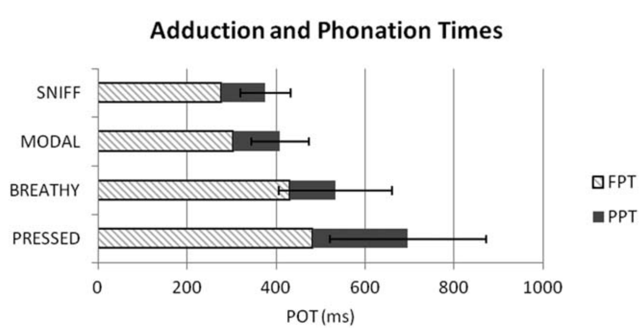


Fig. 5. Adduction and phonation times by phonation type. Mean FPT, PPT, and POT for each phonation type. Error bars show 95% confidence interval for POT on two-tailed Student *t* test, where the margin error for sniff, modal, breathy, and pressed POT are 56, 66, 127, and 175 ms, respectively.
FPT = final phonatory posture time; ms = milliseconds; POT= phonation onset time; PPT= phonatory posture time.

TABLE I.
Descriptive Statistics of Phonation and Frequency Stabilization Times by Student *T* Test Comparison.

		P Values of Mean Difference Between Groups		
	Mean (ms)	Sniff	Modal	Breathy
POT				
Sniff	375.8	–		
Modal	409.1	0.26	–	
Breathy	534.2	**< .01**	0.07	–
Pressed	696.5	**< .001**	**< .01**	0.07
PPT				
Sniff	97.8	–		
Modal	105.7	0.43	–	
Breathy	104.0	0.44	0.49	–
Pressed	213.3	**< 0.05**	0.06	0.05
FPT				
Sniff	278.0	–		
Modal	303.4	0.29	–	
Breathy	430.2	**< 0.05**	0.06	–
Pressed	483.3	**< 0.05**	**< 0.05**	0.31
FST				
Sniff	54.8	–		
Modal	91.8	**< 0.05**	–	
Breathy	183.1	**< 0.0001**	**< 0.01**	–
Pressed	58.6	0.34	0.06	< 0.0001

Bolded values represent $P \leq .05$ when comparing the means between groups.
FPT = final phonatory posture time; FST = frequency stabilization times; POT = phonation onset time; PPT = phonatory posture time.

DISCUSSION

Laryngeal posturing to set up the glottal stiffness and shape of the glottal channel is a critical event in voice production and affects phonation type. In our study, the dynamics of this event were evaluated using concurrent high-speed video and acoustic recording of the larynx from 27 human subjects. This study provides a detailed high-resolution analysis of glottal posturing at phonation onset that has not been reported to date using high-speed photography and the largest number of subjects. The phonation types assessed—breathy, modal (normal), and pressed (hard)—are common types of vocal onset described by voice clinicians, voice teachers, and linguists[21–23] and incorporated into vocal quality assessment tools.[24,25] The differences between these phonation types have been attributed to velocity and duration of glottal adduction.[13]

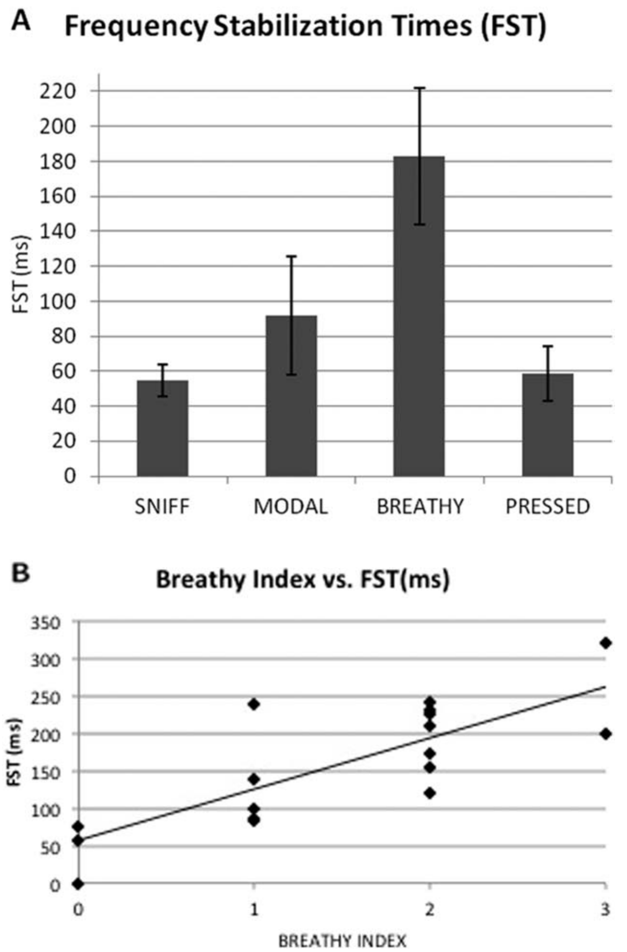


Fig. 6. Frequency stabilization times by phonation type and degree of breathiness.
Frequency stabilization times by phonation type. (A) A trend of increasing FST from pressed to modal to breathy was noted. (B) Frequency stabilization times were significantly correlated with breathy index (Pearson correlation $r = 0.77$, df = 16, $P = < 0.0005$).
df = degrees of freedom; FST = frequency stabilization times.

Sniff-/i/ can possibly be used as a reference for smooth voluntary adduction and phonation onset. Faster closure and phonation onset times were noted with fewer hesitations. Having just performed a sniff maneuver and spring-loaded the glottis and pulmonary system, targeting /i/ phonation is straightforward and quick. Modal voice also appears to be achieved in a similarly fluid manner and the use of modal voice in most laryngeal electromyography studies appears justified. The findings in this study on modal voice are consistent with LEMG findings on calculated POT by Hillel and others.[6,7,26]

Longer phonation onset latencies were found for breathy and pressed phonations. Hillel similarly found longer latencies in dysphonia that could be categorized as pathologically pressed or breathy: abductor spasmodic dysphonia subjects averaged 500 ms and adductor spasmodic dysphonia subjects averaged 530 ms. The author concluded that latencies over 400 ms were abnormal.[6] From a clinical perspective, breathy voice is a very common symptom in a variety of voice disorders, including Parkinson's disease,[8,27–29] and speech language pathologists have successfully used techniques to encourage a more forceful closure.[30]

In our study, breathy voice was always associated with a glottal gap. The closure pattern was characterized by a transition from fast-to-slow glottal closure speed immediately preceding final phonatory posture. In addition, increased rate of hesitations but relatively normal PPT were found. This implies a more cognitively complex task to accurately target the laryngeal posture for a breathy voice quality. It is also possible that the deceleration of glottal closure and maintenance of the glottal gap in breathy voice involves the posterior cricoarytenoid (PCA) because EMG studies demonstrate marked PCA activity in production of voiceless sounds and connected speech that included voiceless sounds.[6,31] If the PCA is involved in regulating the glottic aperture for breathy phonation, it seems logical that a tug-o-war between PCA and lateral cricoarytenoid (LCA) to control the posterior glottic gap would lead to hesitations and slowing in obtaining the final phonatory posture.

Pressed voice is described by increased speed of vocal fold adduction, leading to increased vocal fold impact stress,[32–34] and by high intraglottal contact pressures,[35] leading to phonotrauma.[36,37] In addition, supraglottic hyperactivity is associated with pressed voice.[13] Our results do not support higher speed of closure for pressed voice because FPT was longest in this category. However, intraglottal contact pressures and glottal resistance are likely increased because it took significantly longer to phonation onset after glottal contact. We also observed supraglottic hyperactivity in 64% pressed voice, compared to 11% for modal and 0% for breathy. These movements are common in hyperfunctional voices but are also seen in normal subjects after glottal stops.[38–40] Although this activity alone cannot be considered a precursor to developing vocal fold nodules, there is a higher incidence of supraglottic activity in patients with vocal fold nodules.[38–40] It took longer to reach the final phonatory posture in pressed phonation than the other phonatory types; however, the most significant contribution to the longer phonation onset time was the longer time from final posture to acoustic output. This is likely due to more time needed to achieve the increase in phonation onset pressure required for this phonation type. Interestingly, pressed phonations were the least successfully targeted (40%) based on perceptual ratings.

The FST after phonation onset was notably longer for breathy phonation, followed by modal, and shortest for pressed phonation and sniff-/i/. The onset fundamental frequency and the stable fundamental frequency demonstrated no notable correlations or trends. Frequency stabilization time differs from vocal rise time (the time interval from phonation onset to steady sound intensity)[41] because the endpoint is not stable amplitude but stable frequency. Vocal rise times for breathy and pressed voices are reportedly about 150 and 30 ms, respectively,[41] whereas our frequency stabilization times for breathy and pressed are 183 and 59 ms, respectively. The control of F0 is thought to be primarily regulated by ILMs and secondarily by the subglottic pressure.[14,42–44]

Interestingly, postphonatory pitch shift latencies are reported to be approximately 130 to 150 ms,[45,46] and this is within the breathy phonation frequency stabilization times found in our study, signifying that breathy phonation may utilize a sensory feedback loop.

Cooke et al.[13] and Munhall and Ostry[47] demonstrated, using video (30 frames per second) and ultrasound, respectively, that there is a difference in vocal fold kinematics between pressed, normal, and breathy onsets. They also noted that the pressed (hard) onset was difficult for their subjects to learn, which may in part explain the increased rate of inflection points and the longer PPT that we describe. However, Cooke et al. could not demonstrate a significant difference in total adduction times between gesture types[48] due to their inability to assess the vocal adduction onset and offset. In this study, we were able to analyze phonatory posturing and phonation onset time at high resolution and differentiate between times to achieve FPT versus time spent in the PPT prior to phonation onset, revealing some interesting details. For example, our analysis reveals similar PPT durations between modal and breathy phonation and suggests that breathy phonations may be phenotypically closer to modal phenotype in coordination of respiratory effort than previously believed.[13]

This study has several limitations. The total number of samples included for final analysis was limited by the need to visualize the vocal folds from onset of glottal adduction until acoustic output and for the subjects to accurately target the phonation type. Therefore, the various phonation types (breathy, modal, and pressed) came from unique subjects. However, we do not see this as a potential source of bias in the interpretation of results. In addition, we did not record concurrent electromyographic activities from laryngeal muscles or measure the subglottal pressure. Access to that data would have further illuminated the neuromuscular and aerodynamic interactions underlying the reported findings. Nevertheless, these findings further the understanding of phonation onset dynamics, and may help future evaluations of phonation onset abnormalities in laryngeal pathologies.

CONCLUSION

Via the complex interactions of the intrinsic muscles of the larynx, vocal folds efficiently adduct for airway protection, deglutition, cough, and phonation. Many disease states can alter the dynamics of vocal fold adduction, leading to dysphonia and dysphagia. This study provides the first high-resolution assessment of phonatory types and characteristic laryngeal dynamics. The patterns and differences seen here, as normal subjects attempt to create breathy or pressed voices, may help explain the pathophysiology of neurocognitive disorders of the voice. Future high-resolution evaluation of laryngeal posturing in patients suffering from neurodegenerative voice disorders may reveal key targets for therapeutic intervention.

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