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Differential Roles for the Thyroarytenoid and Lateral Cricoarytenoid Muscles in Phonation

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Objectives/Hypothesis: Laryngeal adductor muscle dysfunction is a common cause of voice disorders. Reconstitution of adductor muscle function is often the target of therapy, but the effects of these muscles on voice production remain to be fully understood. This study investigated the differential roles of thyroarytenoid (TA) and lateral cricoarytenoid (LCA) muscles on voice production.

Study Design: Basic science study using an in vivo canine model of phonation.

Methods: The TA and LCA muscle nerve branches were stimulated to obtain seven graded levels of muscle activation, from threshold to maximal contraction. The effects of LCA muscle activation alone, TA muscle activation alone, and combined TA and LCA muscle activation on phonation onset parameters were investigated. Phonatory posture, phonation onset type, fundamental frequency (F0), phonation onset pressure, and airflow were evaluated.

Results: LCA muscle activation closed the posterior glottis, but the midmembranous gap remained. TA muscle activation closed the membranous glottis, but the posterior gap remained. Complete glottal closure was obtained only with combined TA and LCA muscle activation. Phonation onset with the LCA muscle alone was characterized by multiple modes (soft, aperiodic, periodic), whereas with the TA muscle alone it was abrupt and periodic but had significant baseline noise. Combined muscle activation led to elimination of baseline noise with stable abrupt periodic onset of phonation. Combined muscle activation was also necessary for F0 variation. The LCA muscle assisted the TA muscle in increasing subglottal pressure while concurrently reducing phonation onset airflow.

Conclusions: The TA muscle is necessary for F0 variation, stable onset phonation, and increased subglottal pressure, but needs the LCA muscle for optimal effectiveness and to reduce airflow requirements with increased activation.

Key Words: Thyroarytenoid, lateral cricoarytenoid, speech production, in vivo phonation, canine.

Level of Evidence: NA

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INTRODUCTION

Voice production requires coordinated neuromuscular activation of the intrinsic laryngeal muscles (ILMs) to set up the glottal phonatory posture (shape) and stiffness. Aerodynamic energy then matches the subglottal pressure and transglottal airflow required for onset of phonation. Neuromuscular control plays a greater role than aerodynamic control in determining acoustic parameters such as fundamental frequency (F0).[1,2] Among the ILMs, it is generally understood that the thyroarytenoid (TA), lateral cricoarytenoid (LCA), and interarytenoid (IA) muscles adduct the vocal folds to narrow the glottic inlet and facilitate rise of sufficient subglottal pressure for phonation, whereas the cricothyroid (CT) muscle elongates the vocal fold for F0 control.[3] However, in vivo studies evaluating the differential roles for the TA muscle and particularly the LCA muscle in phonation are severely lacking.

In many laryngeal diseases causing dysphonia, the TA and LCA muscles are the most commonly affected. Reconstitution of the physiologic actions of these muscles is also the major goal in medical and surgical intervention. For example, these muscles are atrophic or hypofunctional in presbylarynx, paresis, and paralysis conditions, and hyperfunctional in adductor spasmodic dysphonia. Surgical intervention for hypofunction such as type 1 thyroplasty primarily mimics TA muscle activation, whereas arytenoid adduction mimics LCA muscle activation. Other procedures, such as laryngeal reinnervation using ansa cervicalis to recurrent laryngeal nerve anastomosis for paralysis, nonspecifically target both muscles.

If therapeutic interventions are geared toward reconstituting the actions and effects of laryngeal muscle activation, then the roles of those muscles in phonation should be fully understood. For example, because both TA and LCA muscles are laryngeal adductors, what are their respective roles and why are both muscles needed? Despite the widespread procedures targeting the LCA

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and TA muscles, very little is known about their interactions and critical functions. If glottal closure alone is the critical requirement for normal phonation, then LCA muscle procedures might be adequate. In that setting the role for TA muscle activation is unclear. The fundamental question, how do TA and LCA muscles differ in their roles in control of voice production, has not been investigated. How do they interact? What are the aerodynamic consequences? In this study, the differential roles of the TA and LCA muscles on phonation onset were evaluated by systematic activation of these muscles in an in vivo canine model.

MATERIALS AND METHODS

In Vivo Canine Model

This animal study protocol was approved by the Institutional Animal Research Committee of the University of California, Los Angeles. Surgical exposure of the larynx and the individual distal nerve branches of the individual laryngeal nerves was as described previously.[2,4] Appropriately sized tripolar cuff electrodes (Ardiem Medical, Indiana, PA) were applied to the respective nerve branches to stimulate the TA, LCA/IA, and the CT muscles separately. As described previously, the IA muscle nerve branch cannot be divided without excessive laryngeal dissection that can potentially damage the muscles being tested.[2] Thus, the LCA and IA muscles were stimulated as a single complex, and the contribution of the IA muscle is expected to be minimal compared to the LCA muscle as previously described.[5] The nerve branches to the posterior cricoarytenoid muscle, Galen's anastomosis, and the internal superior laryngeal nerve branches were divided bilaterally to eliminate their effects during nerve stimulation.

A subglottal tube to provide rostral airflow for phonation was attached to the trachea at ring 2 to 3 and connected to an airflow controller (MCS Series Mass Flow Controller; Alicat Scientific, Tucson, AZ), which was used to increase the airflow rate linearly from 300 to 1600 mL/s during the 1,500-ms nerve-stimulation duration. The airflow was increased in such a manner to continuously increase subglottic pressure (P_{sub}) to reach phonation onset pressure (P_{th}) and beyond until maximal airflow level was reached. The airflow at the glottic level was warmed to 37.5°C and 100% humidity using a heated humidifier (HumiCare 200; Gruendler Medical, Freudenstadt, Germany).

In this investigation, the differential effects and interactions of the LCA and TA muscles on phonation onset characteristics were investigated. First, the LCA muscles alone were symmetrically stimulated bilaterally over seven levels of graded stimulation, from threshold muscle activation (level 1, where just a hint of vocal fold movement or strain change was observed) to maximal activation (level 7, where maximal vocal fold displacement or strain change was observed).[6] Then the TA muscles alone were similarly stimulated over seven levels. Subsequently, LCA muscle activation was kept constant at several levels (levels 1, 3, 5), whereas TA muscle activation was increased over seven levels. Several LCA/TA muscle combinations were repeated with CT muscle activation, but interactions with CT muscles was not a focus of this study and was not comprehensively studied. Neuromuscular stimulation duration for each condition was 1,500 ms with 0.1-ms-long unipolar cathodic pulses at a repetition rate of 100 Hz. To allow muscle recovery and transfer of high-speed video (HSV) data to the host computer, each stimulation pulse train was followed by a 3.5-s pause prior to next stimulation with the next activation condition.

Measurement of Experimental Parameters (F0, P_{th}, Airflow)

Acoustic and aerodynamic data were recorded using a probe tube microphone (Model 4128; Bruel & Kjaer North America, Norcross, GA) and a pressure transducer (MKS Baratron 220D; MKS Instruments, Andover, MA) mounted flush with the inner wall of the subglottic inflow tube about 5 cm below the inferior border of the glottis. The subglottal acoustic pressure signal was used to determine F0 at phonation onset using Sound Forge acoustic analysis software (Sonic Foundry Sound Forge Version 6.0; Sonic Foundry Inc., Madison, WI) as described previously.[2,4] The acoustic signal and digital video kymograms (DVK) of glottal vibration were simultaneously displayed on a computer screen to evaluate and categorize the characteristics of the acoustic signal as well as the vibratory pattern. The time instance of phonation onset was determined using the acoustic signal and confirmed by DVK to ensure that acoustic signal correlated with glottal vibration. The corresponding mean P_{sub} at phonation onset represented the P_{th}. The corresponding airflow at phonation onset was also recorded.

A high-speed digital video camera (Phantom v210; Vision Research Inc., Wayne, NJ) imaged laryngeal deformation and vibration at 3,000 fps for the duration of nerve stimulation. The distance from the camera to the larynx remained constant for all conditions. India ink was used to mark several landmarks on the vocal fold surface, including the vocal processes. DVK was generated using custom-programmed Python software. The HSV was used to generate the DVKs.

To keep data scales consistent, data from one animal are presented. Findings are consistent from two other animals and where the role of ILMs in register control was studied.[2,4] Results of this study shed new light in the mechanisms of voice production, as well as have applications for medical and surgical therapeutic procedures where the actions of the TA and LCA muscles are targeted.

RESULTS

Effects on Phonatory Posture

The two laryngeal adductor muscles affected the prephonatory posture differently (Fig. 1). With symmetric TA muscle activation alone, there was midmembranous closure but a large posterior glottal gap remained (Fig. 1A). In contrast, the posterior glottal gap was closed upon LCA/IA muscle activation, but a midmembranous gap remained (Fig. 1B). Complete membranous and cartilaginous glottal closure was achieved with combined activation of both the TA and LCA/IA muscles (Fig. 1C).

Effects on Vibration

Glottal vibratory characteristics at phonation onset are presented in Figure 2, where concurrent acoustic signal is overlaid with the corresponding DVK for three illustrative conditions. Phonation onset with activation of the LCA/IA muscles alone was characterized by three vibratory modes (Fig. 2A). Immediately after adequate glottal closure was achieved, a low-amplitude periodic

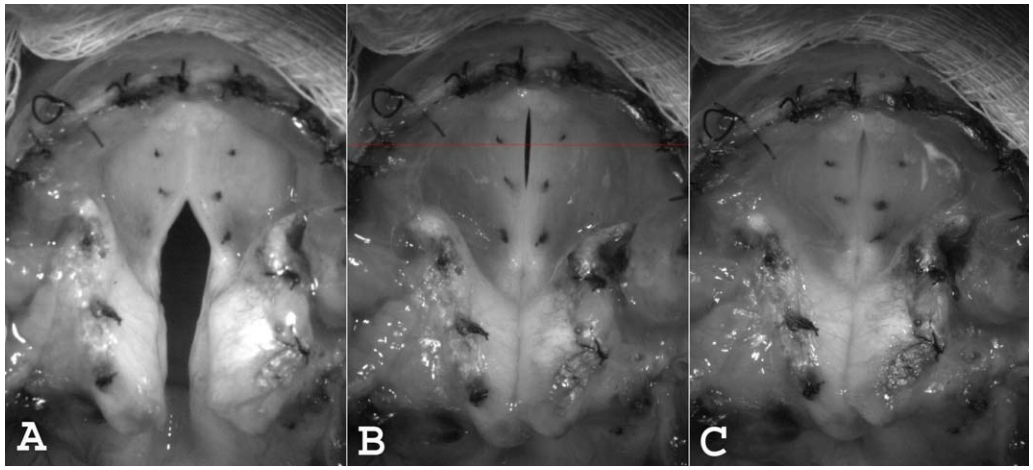

Fig. 1. Effects on prephonatory posture with symmetric activation of (A) the bilateral TA muscle alone (level 3), (B) the bilateral LCA/IA muscle alone (level 4), and (C) the combined bilateral TA (level 3) and bilateral LCA/IA (level 5) muscles. The thin horizontal line across the midmembranous area in (B) represents the general location of the line for digital kymography. IA = interarytenoid; LCA = lateral cricoarytenoid; TA = thyroarytenoid. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

oscillation commenced ("soft" onset). This soft onset vibration was limited to the medial edges of the glottis and was present for all but the highest (level 7) and the lowest (level 1) LCA muscle activation levels. This vibratory mode was followed by aperiodic vibration of variable duration that was present in all but the lowest

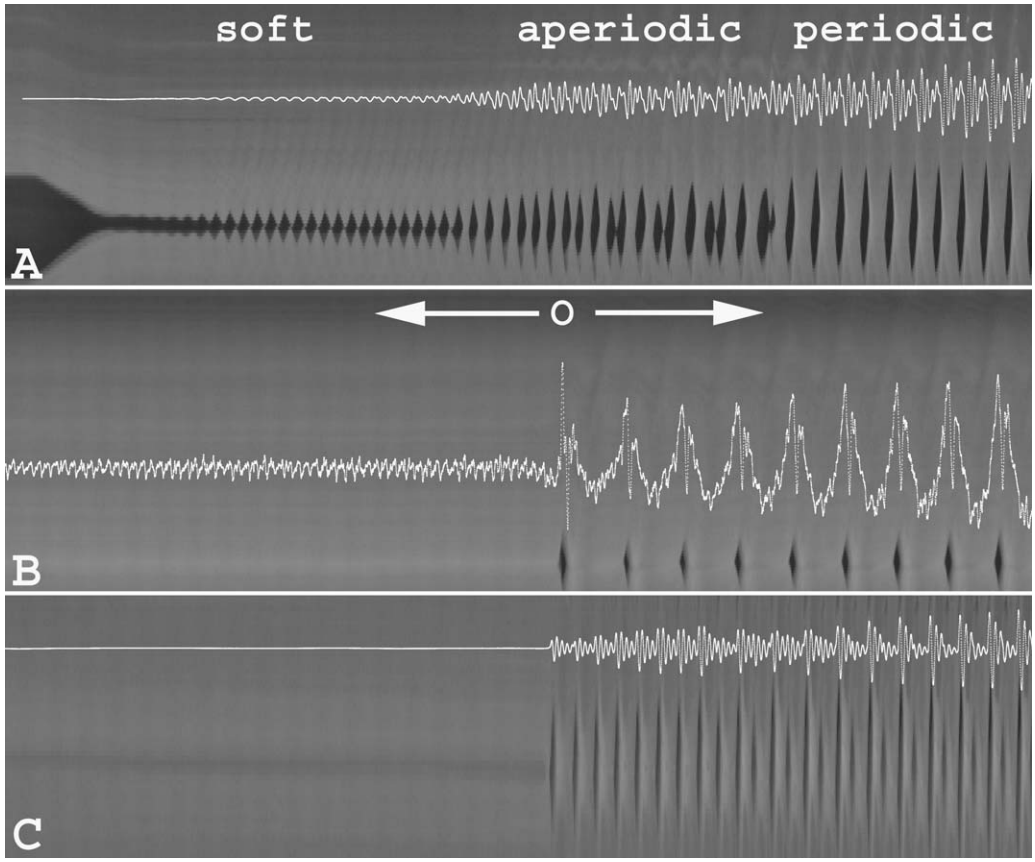

Fig. 2. Digital kymography with concurrent overlay of acoustic signal illustrating vibratory characteristics at phonation onset upon activation of (A) the bilateral LCA/IA muscle alone (level 4), (B) the bilateral TA muscle alone (level 4), and (C) the combined bilateral LCA/IA (level 5) and bilateral TA (level 3) muscles. See the text for descriptions of vibratory characteristics. IA = interarytenoid; LCA = lateral cricoarytenoid; O = phonation onset; TA = thyroarytenoid.

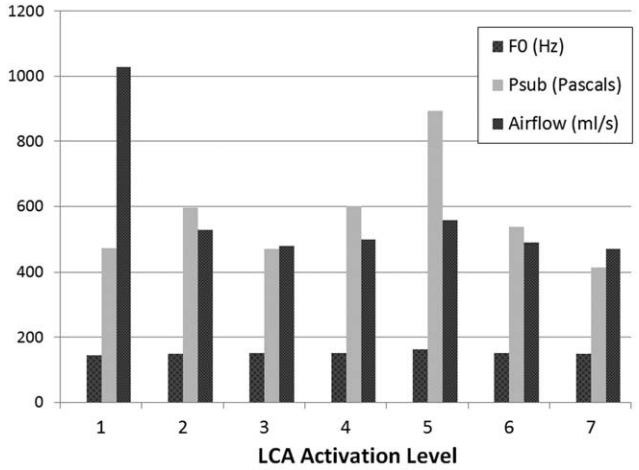

Fig. 3. Fundamental frequency and aerodynamic parameters at the onset of periodic vibration with graded levels of symmetric LCA muscle activation alone, from threshold activation (level 1) to maximal activation (level 7). F0 = fundamental frequency at periodic voice onset; LCA = lateral cricoarytenoid; Psub = subglottal pressure.

activation (level 1). Subsequently, as subglottal pressure increased, regular periodic vibration ensued until the end of nerve stimulation.

Unlike the triphasic phonation onset described above with LCA muscle activation alone, vibration with symmetric TA muscle activation alone was characterized by an abrupt onset of periodic vibration (Fig. 2B). However, prior to onset of membranous vocal fold vibration, the acoustic signal displayed fine low-amplitude high-frequency baseline signal ("baseline noise"). Review of HSV revealed fine mucosal oscillation of the open posterior cartilaginous glottis as the source of this noise (see open posterior glottis in Fig. 1A). The baseline noise component disappeared completely upon activation of both the TA and LCA/IA muscles, and posterior glottic closure was achieved. Phonation onset was abrupt and periodic throughout, even starting at TA muscle activation level 1. Phonation onset was always abrupt and periodic when the TA muscle was active, but when the posterior glottic gap was present, the noise signal was always present.

Effects on F0

The F0 range of periodic vibration with LCA muscles alone was along a narrow and relatively flat range of 145 to 165 Hz (Fig. 3). In contrast, the effects of TA muscle activation on F0 depended on the LCA muscle activation level (Table I). When LCA muscle activation was absent (level 0) or low (level 1), increasing TA

TABLE I.
Fundamental Frequency, Subglottic Pressure at Periodic Onset, and Airflow at Periodic Onset at Various TA and LCA Muscle Levels Without Cricothyroid Muscle Activation.

Fundamental frequency (Hz)

Level	TA 0	TA 1	TA 2	TA 3	TA 4	TA 5	TA 6	TA 7
LCA 0	NP	153	54	63	64	65	66	67
LCA 1	144	96	104	79	74	82	97	89
LCA 3	171	143	137	138	176	184	222	218
LCA 5	163	137	154	167	191	242	265	285

Phonation onset pressure (Pa)

Level	TA 0	TA 1	TA 2	TA 3	TA 4	TA 5	TA 6	TA 7
LCA 0	NP	366	859	989	1,132	1,387	1,581	1,550
LCA 1	396	239	857	1,151	1,562	1,871	2,131	2,191
LCA 3	818	229	1,029	1,308	1,747	2,190	3,117	3,022
LCA 5	460	289	1,001	1,322	1,695	2,127	2,414	2,977

Phonation onset airflow (mL/s)

Level	TA 0	TA 1	TA 2	TA 3	TA 4	TA 5	TA 6	TA 7
LCA 0	NP	878	1,063	1,260	1,354	1,272	1,465	1,486
LCA 1	822	445	584	695	749	816	955	991
LCA 3	583	376	547	592	667	711	835	827
LCA 5	478	396	514	553	579	638	665	695

100 Pa is at 1 cm H_20.
LCA = lateral cricoarytenoid; TA = thyroarytenoid.

muscle activation led to decrease in F0. When LCA muscle activation level was higher (levels 3 and 5), increasing TA muscle activation resulted in F0 increase (range, 137–285 Hz) (Table I).

Effects on Phonatory Aerodynamics

As mentioned above, glottal vibration with bilateral LCA muscles alone was characterized by a triphasic vibratory mode at phonation onset. A small-amplitude vibration (soft onset) occurred at a very low P_{sub} range of 20 to 144 Pa (0.2–1.47 cm H_20). As P_{sub} increased, the small amplitude vibration was followed by a short duration aperiodic vibration before settling into periodic vibration for the duration of the stimulation (Fig. 2A). The range of P_{sub} for periodic vibration with LCA muscle activation alone was within a narrow range (416–603 Pa) except for one outlier, level 5, at 895 Pa (Fig. 3). Onset airflow was higher at activation level 1 (1,030 mL/s) due to large glottal gap, but then settled to a narrow range for the rest of the activation levels (471–559 mL/s) as posterior glottic closure was achieved (Fig. 3).

TA muscle activation had a consistent effect on phonation onset P_{sub} and airflow, regardless of LCA muscle level (Table I). Increasing TA muscle activation at a constant LCA muscle level led to increase in both P_{th} and airflow. However, increasing the LCA muscle level at a constant TA muscle level led to an increase in P_{sub} but a decrease in airflow (Table I). Thus, TA and LCA muscles were synergistic for P_{th} but antagonistic for airflow. These results were more apparent with increasing levels of both TA and LCA muscle activation.

DISCUSSION

In this study, the differential roles of the TA and LCA muscles on phonation onset were investigated in an established in vivo model canine model of phonation.[2,4,7] These results reveal specific roles for these adductor muscles. The LCA muscle is needed to close the posterior gap and reduce the phonation onset airflow. Maximal phonation time is limited by pulmonary vital capacity, and therefore posterior glottal closure by the LCA muscle allows frugal use of pulmonary vital capacity. However, phonation onset with LCA muscles alone transitions through multiple vibratory modes, and also lacks F0 and subglottal pressure modulation over the range of activations. These acoustic and aerodynamic findings for LCA muscle activation has been corroborated in human ex vivo larynx models, where LCA muscle activation can be modeled but not TA muscle activation.[8] Thus, the voice with LCA muscles alone is monotonous in pitch and loudness. The TA muscles can modulate these latter voice parameters by introducing glottal tension; however, they rely on the LCA muscles to most effectively accomplish these tasks. Vibration with TA muscles alone resulted in a contracted F0 range, reduced F0, increased subglottal pressure, increased airflow, with prominent baseline flow noise prior to phonation onset. Thus, voice production with TA muscles alone would also be a low-pitched monotonous tone with reduced phonation time due to a large posterior glottic gap.

The LCA muscle acts as the "great assistant" to the TA muscle. With the help of the LCA muscle, the TA muscle is able to generate a greater range of F0 and P_{sub}. Most importantly, the LCA muscle allows the TA muscle to achieve these parameters with increased efficiency and without a penalty of increased airflow. LCA muscle activation decreases phonation onset airflow and thus would be expected to play the most significant role in increasing maximal phonation time. An interesting finding in this study is that LCA and TA muscles were synergistic in increasing F0. This makes sense anatomically, as the LCA muscle is able to hold the vocal fold "steady" at one end in an adducted positon, while the TA muscle adds stiffness to the glottis. Without LCA muscle activation, TA muscle activation would simply shorten the glottis, and the resulting laxity of the cover layer would lower F0, as seen in this study. As would be expected, the LCA muscle is more effective in this role as its activation level increases. Another important contribution of the TA muscle is to generate an abrupt periodic phonation onset, an important consideration especially in singing. Phonation onset characteristics were best when both the TA and LCA muscles were activated.

These findings have implications for treatment of laryngeal dysfunction involving the TA and LCA muscles. In the treatment of vocal fold paralysis, this study would support combined procedures to close the membranous and cartilaginous glottis. For example, a combined type 1 thyroplasty and arytenoid adduction would be expected to have better results compared to either procedure alone. However, the study also points out some limitations of such static procedures. Because only one stiffness level can be introduced to the system with static procedures, interventions that control glottal stiffness dynamically, such as laryngeal reinnervation, would be expected to have improved F0 and intensity control. Procedures such as arytenoid adduction combined with laryngeal reinnervation currently have the best potential for vocal rehabilitation of unilateral paralysis, as adduction would statically mimic LCA muscle action at the posterior glottis, and reinnervation would provide some dynamic TA muscle control. Further studies are needed to evaluate this hypothesis. In regard to the treatment of hyperfunctional disorders, it is clear that the TA muscle is necessary to increase P_{sub}, and the LCA muscle alone is unable to do so. However, the LCA muscle is synergistic with the TA muscle in this regard, and the TA muscle alone is not as effective. Thus, both muscles are potential targets (e.g., for Botox injection).

CONCLUSION

The roles and interactions of the laryngeal adductor muscles in phonation have not been previously evaluated. Using an in vivo canine model of phonation, the effects of the TA and LCA muscles on phonation onset characteristics was studied. Alone, neither the TA nor LCA muscles were effective in F0 variation. The TA muscle is able to add tension to the glottis and increase the P_{sub}. However,

the LCA muscle is essential for the TA muscle to be effective in varying the F0 and increasing P_{sub}, while concurrently reducing the airflow requirement. P_{sub} is one of the main physiological variables controlling vocal loudness.[9] It would thus be expected that for voice production to be louder and efficient, both muscles are necessary.

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