The Laryngoscope
© 2017 The American Laryngological,
Rhinological and Otological Society, Inc.

Hirano's Cover–Body Model and Its Unique Laryngeal Postures Revisited

Andrew M. Vahabzadeh-Hagh, MD; Zhaoyan Zhang, PhD; Dinesh K. Chhetri, MD

Objectives/Hypothesis: In 1974, Minoru Hirano proposed his theory of voice production that is now known as the cover–body theory. He described the thyroarytenoid (TA) and cricothyroid (CT) muscles as the major determinants of vocal fold shape and stiffness, and theorized four typical laryngeal configurations resulting from unique TA/CT activations, with implications for the resulting voice quality. In this study, we directly observed the vocal fold medial surface shape under Hirano's unique TA/CT activation conditions to obtain a three-dimensional (3D) understanding of these laryngeal configurations during muscle activation.

Study Design: In vivo canine hemilarynx model.

Methods: Flesh points were marked along the medial surface of the vocal fold. Selective TA and CT activation were performed via respective laryngeal nerves. 3D reconstructions of the vocal fold medial surface were derived using digital image correlation.

Results: Low level TA and CT activation yielded anteroposterior lengthening and vertical thinning of the vocal fold. When TA activation is far greater than CT, the vocal fold shortens and thickens. With slightly greater TA than CT, activation the vocal length is maintained on average, whereas its vertical thickness decreases. With CT far greater than TA activation, the vocal fold lengthens and thins. In all conditions, glottal contour changes remained minimal.

Conclusions: Analysis of the 3D geometry of the vocal fold medial surface under Hirano's four typical laryngeal configurations revealed that the key geometric changes during TA/CT interactions lie within the anteroposterior length and the vertical thickness of the vocal fold.

Key Words: Larynx, voice, canine, cover–body, vocal fold, vocal register, intrinsic laryngeal muscle, Hirano.

Level of Evidence: NA.

***Laryngoscope*, 128:1412–1418, 2018**

INTRODUCTION

The human larynx, a single sound generator, is capable of producing a voice of tremendous variety in pitch, intensity, and quality. In the 1970s, Minoru Hirano set out to understand how singers can produce such variety in voice using only a single set of vocal folds. In 1974, Hirano published the cover–body theory of vocal fold vibration. Here he described the unique morphological structure of the vocal folds and divided them biomechanically into the body and the cover layer. The main substance of the vocal fold is the thyroarytenoid (TA) muscle. The TA muscle, innervated by the recurrent laryngeal nerve, has mechanical properties that vary with activation. Overlying the TA muscle is the elastic conus, or vocal ligament. This fibrous vocal ligament interdigitates with vocalis muscle fibers allowing the TA muscle and vocal ligament to function as a single vibratory unit (body) during phonation. Superficial to the body lies the vocal fold epithelium and superficial layer of the lamina propria loosely associated with the vocal ligament. The superficial lamina propria and epithelium move as a vibratory unit (cover) weakly coupled to the body. Therefore, this cover–body theory of vocal fold vibration dictates the vocal folds function at least as a double-structured vibrator.

The mechanical properties of the vocal fold are primarily determined by the intrinsic laryngeal muscles. Hirano recognized that the TA muscle controlled body stiffness, and TA muscle interaction with the cricothyroid (CT) muscle controlled tension of the vocal fold cover layer. He then described four typical laryngeal adjustments achieving unique relationships between the body and cover for combinations of TA muscle and CT muscle activation. These four laryngeal adjustments traverse the gamut of voice production, characterized by different vocal registers and intensities, demonstrating how the vocal folds function as many different sound generators.[1,2]

Vocal registers are defined by a series of frequencies of similar quality produced through common physiologic means.[3] Vocal registers include glottal fry, modal, chest, head, falsetto, and whistle registers. Vocal registers may be referred to as light, such as head or falsetto registers,

---

From the Department of Head and Neck Surgery, University of California Los Angeles David Geffen School of Medicine, Los Angeles, California, U.S.A.

Editor's Note: This Manuscript was accepted for publication on October 16, 2017.

Presented as an oral presentation at the American Laryngological Association's 2017 Spring Meeting at COSM, San Diego, California, U.S.A., April 26–28, 2017.

The authors have no other funding, financial relationships, or conflicts of interest to disclose.

Send correspondence to Andrew M. Vahabzadeh-Hagh, MD, 10833 Le Conte Avenue, 62-132, Los Angeles, CA 90095. E-mail: avahabzadehHagh@mednet.ucla.edu

DOI: 10.1002/lary.27000

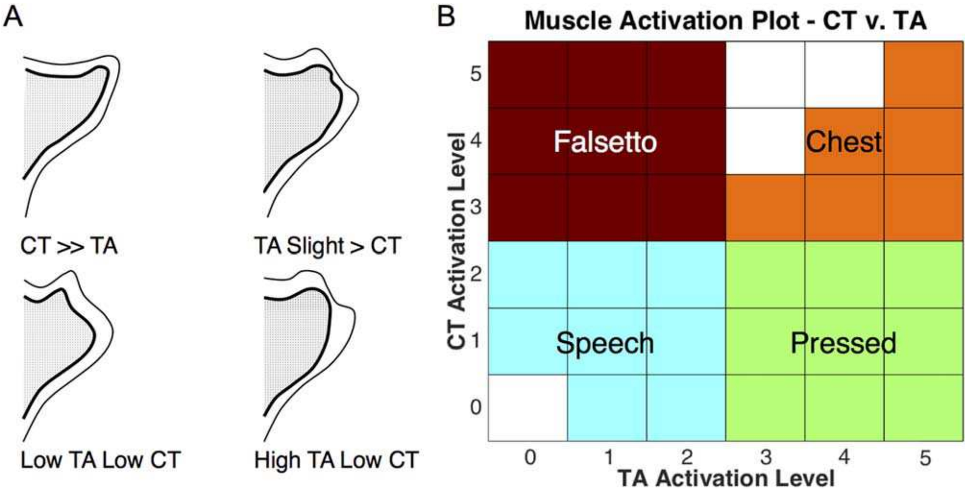

Fig. 1. Hirano's four laryngeal conditions. (A) Hirano's four laryngeal adjustments as labeled are presented as coronal sections through the left vocal fold. Cover is represented as the outer white layer, whereas the body is the inner patterned section. Condition 1 (A, lower left), Low TA Low CT, occurs with weak activation of the TA and CT muscles. Hirano describes this as producing soft phonation with a small elastic constant for the body and cover. Condition 2 (A, lower right), High TA Low CT, occurs when the TA muscle contracts much more than the CT muscle, producing loud heavy voice. The body is stiff whereas the cover has slack. Condition 3 (A, upper right), TA Slight > CT, occurs when TA muscle contraction is slightly more dominant than the CT muscle, producing heavy or modal register voice. Condition 4 (upper left), CT >> TA, occurs when CT muscle contraction is much greater than the TA muscle, yielding light register or falsetto. The body and cover are passively stretched producing a high elasticity constant. Recreated from Hirano 1974.[1] (B) Muscle activation plot of CT versus TA muscle showing the grouping of TA and CT muscle combinations to fit Hirano's four conditions. CT and TA muscle activation levels span from 0 (inactive) to 5 (maximum activation). Condition 1, includes TA and CT muscle activation levels 0 to 2 (n = 8, blue). Condition 2, High TA Low CT, includes TA muscle activation levels 3 to 5 and CT muscle levels 0 to 2 (n = 8, green). Condition 3, TA muscle slightly greater activation than CT muscle (TA Slight > CT), includes TA and CT muscle levels 3 to 5 (n = 6, orange). Lastly, condition 4, CT muscle activation much greater than TA muscle (CT >> TA), includes TA muscle levels 0 to 2 and CT muscle levels 3 to 5 (n = 7, red). Titze originally introduced the idea of muscle activation plots, which he organized into four quadrants as labeled (speech, falsetto, chest, and pressed). These four voice quadrants resemble Hirano's four laryngeal adjustments. Based on Titze's *Principles of Voice Production*.[10] CT = cricothyroid; TA = thyroarytenoid. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

or heavy, such as chest register. Current theories suggest that register control is a primary laryngeal event, dependent upon laryngeal muscle activity, vocal fold adduction, and glottal shape.[4] Hirano's first laryngeal adjustment corresponds to low level TA muscle and CT muscle activation (Low TA Low CT) producing soft phonation. The body and cover are flexible and both involved in vibration. The second laryngeal adjustment corresponds to a much greater TA muscle than CT muscle (High TA Low CT). This results in a stiff body and slackened cover, producing loud heavy voice. The third adjustment corresponds to a slightly greater TA muscle activation than CT muscle (TA Slight > CT). This yields heavy or modal register, and vocal fold deformation is evenly shared between body and cover. The fourth adjustment corresponds to very low TA muscle activation with high level CT muscle (CT >> TA). This results in passive stretching of the body and cover achieving light or falsetto register. In his 1974 publication, Hirano provides a coronal pictorial representation of these four laryngeal adjustments (Fig. 1A). He alludes to the importance of the vocal fold medial surface shape in his images, but this remains to be quantitatively described. In this report, we use an in vivo canine hemilarynx model to directly measure vocal fold adduction, thickness, and length. We provide precise and graded stimulation of the TA and CT muscles over 36 activation combinations to fully characterize changes in glottal shape as they relate to Hirano's four laryngeal paradigms and vocal registers.

MATERIALS AND METHODS

This study was approved by the Institutional Animal Care and Use Committee. One mongrel canine was used. The laryngotracheal framework was exposed in the neck as previously described.[5–8] Tracheostomy was performed followed by an infrahyoid pharyngotomy and pharyngeal division. A right hemilaryngectomy was performed exposing the left vocal fold. India ink was used to mark flesh points spaced 1.3 mm apart (flesh point diameter = 130 to 220 μm) in a grid-like fashion along the vocal fold medial surface. The hypotenuse of a glass right-angled prism abutted the anatomic glottal midline. The prism allowed two distinct views of the vocal fold medial surface captured by a high-speed digital camera.

Mapping functions for three-dimensional (3D) analysis were calculated by calibrating the camera (384 × 672 pixel resolution; 0.04 mm/pixel) to a standardized calibration plate as previously described.[7–9] These mapping functions helped create 3D contour plots of the vocal fold medial surface from which adduction, thickness, and length were measured.

The recurrent laryngeal nerve branch to the TA muscle and the external branch of the superior laryngeal nerve to the CT muscle were isolated, ligated, and fashioned with a cuff electrode for stimulation as previously described.[7,8] Graded stimulation of the TA and CT muscles were performed over 8 levels, from zero, no activation, to 7, maximal activation. Both TA and CT muscles saturated their glottal shape deformation at activation level 5. As such, we studied all combinations of TA and CT muscles from activation level 0 to 5 (36 combinations). Vocal fold deformation was captured at 3,000 frames per second with a high-speed digital camera (Phantom v210; Vision Research, Inc., Wayne, NJ).

The image-processing program DaVis version 7.2, (LaVision Inc., Goettingen, Germany) was used for time series cross-correlation analysis for 3D deformation calculations of the medial surface for the 36 TA and CT muscle combinations.[7,8] From surface height measurements, vocal fold adduction, thickness, and length were extracted. We grouped TA and CT muscle activation combinations with each of Hirano's laryngeal adjustments. Condition 1, Low TA Low CT, includes TA and CT muscle activation levels 0 to 2 (n = 8). Condition 2, High TA Low CT, includes TA muscle activation levels 3 to 5 and CT muscle levels 0 to 2 (n = 8). Condition 3, TA Slight > CT, includes TA and CT muscle levels 3 to 5 (n = 6). Lastly, condition 4, CT >> TA, includes TA muscle levels 0 to 2 and CT muscle levels 3 to 5 (n = 7).

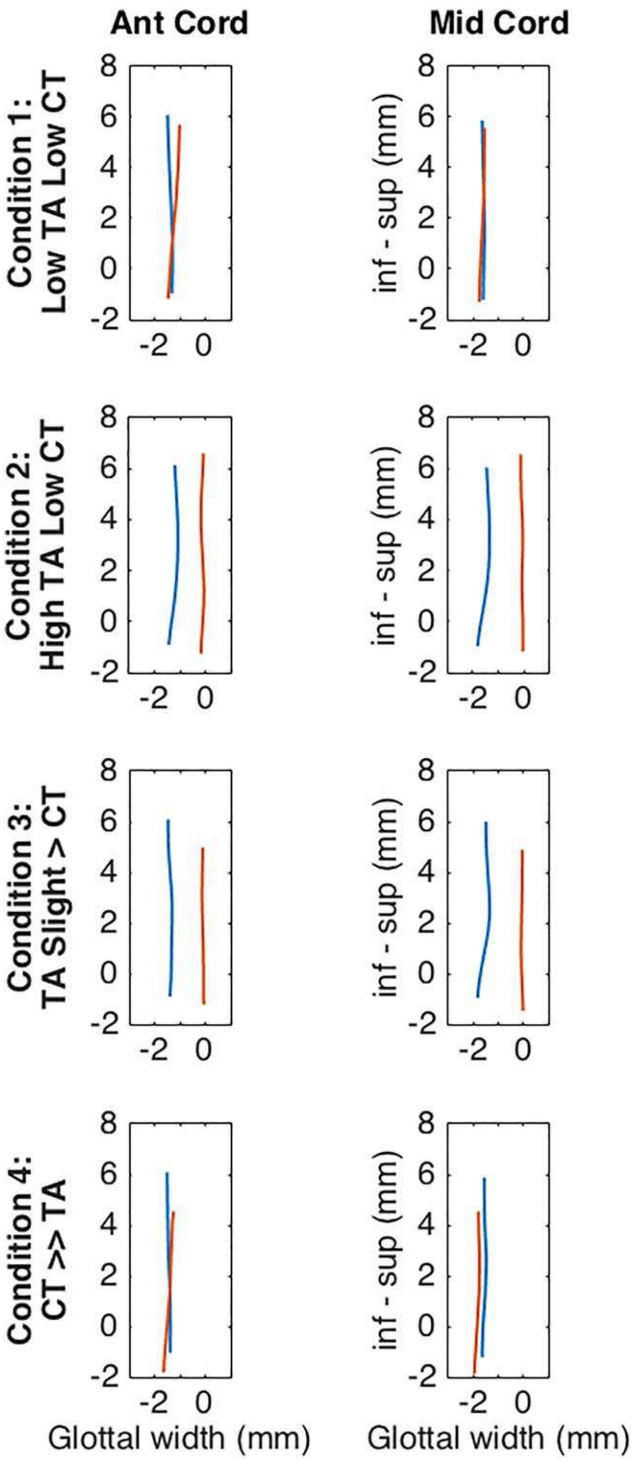

Fig. .2.

Fig. 2. Coronal sections of the vocal fold medial surface for Hirano's four adjustments. A representative combination of TA and CT was chosen for each of Hirano's four conditions. Condition 1, Low TA Low CT, was TA level 1 and CT level 1. Condition 2, High TA Low CT, was TA level 5 and CT level 1. Condition 3, TA Slight > CT, was TA level 5 and CT level 4. Condition 4, CT >> TA, was TA level 1 and CT level 3. The first column includes coronal sections through the anterior vocal fold (Ant Cord), a point halfway between the mid membranous vocal fold and the anterior commissure. The second column incudes coronal sections through the mid membranous fold (Mid Cord). Conditions 1 to 4 are presented on rows 1 to 4, respectively. Blue lines are the resting coronal section (0 ms), whereas red lines are the final prephonatory coronal posture obtained 117 ms after stimulation onset. Axes are equal. Condition 1 yields slight convergent configuration. Conditions 2 and 3 yield near complete vocal fold adduction. Condition 4 yields slight abduction of the Mid Cord. Ant Cord = Anterior vocal fold; CT = cricothyroid; Mid Cord = mid membranous vocal fold; TA = thyroarytenoid. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

RESULTS

In Hirano's 1974 publication he drew four laryngeal configurations that he felt pictorially represented the vocal fold as a double-structured vibrator capable of different vocal registers and pitch. Figure 1A recreates these coronal sections. Condition 1, Low TA Low CT, represents a flexible body and cover. Condition 2, High TA Low CT, represents a firm, stiff body with a slackened cover. In condition 3, TA Slight > CT, the body and cover contribute to vocal fold vibration producing heavy or modal register. Condition 4, CT >> TA, represents a maximally stretched body and cover.

In Titze's *Principles of Voice Production*, he described the concept of muscle activation plots.[10] Namely, a plot of the percent maximum CT muscle activity versus percent maximum TA muscle activity. He divided these plots into four quadrants that spanned the gamut of vocal registers (e.g., pressed, chest, speech/modal, and falsetto) much as Hirano's four laryngeal configurations did. Figure 1B provides a muscle activation plot showing the array of TA and CT muscle combinations we evaluated in this report. Here we looked at TA and CT muscle activation from level 0, inactive, to level 5, maximally active. Based on Hirano's four configurations, we then grouped different TA and CT muscle combinations into one of these four conditions.

Using our hemilarynx model, we set out to quantitatively recreate the glottal coronal sections for Hirano's four conditions. Figure 2 demonstrates the coronal sections through two points along the A-P axis of the vocal fold; the mid membranous vocal fold (mid cord) and a point midway between the mid fold and the anterior

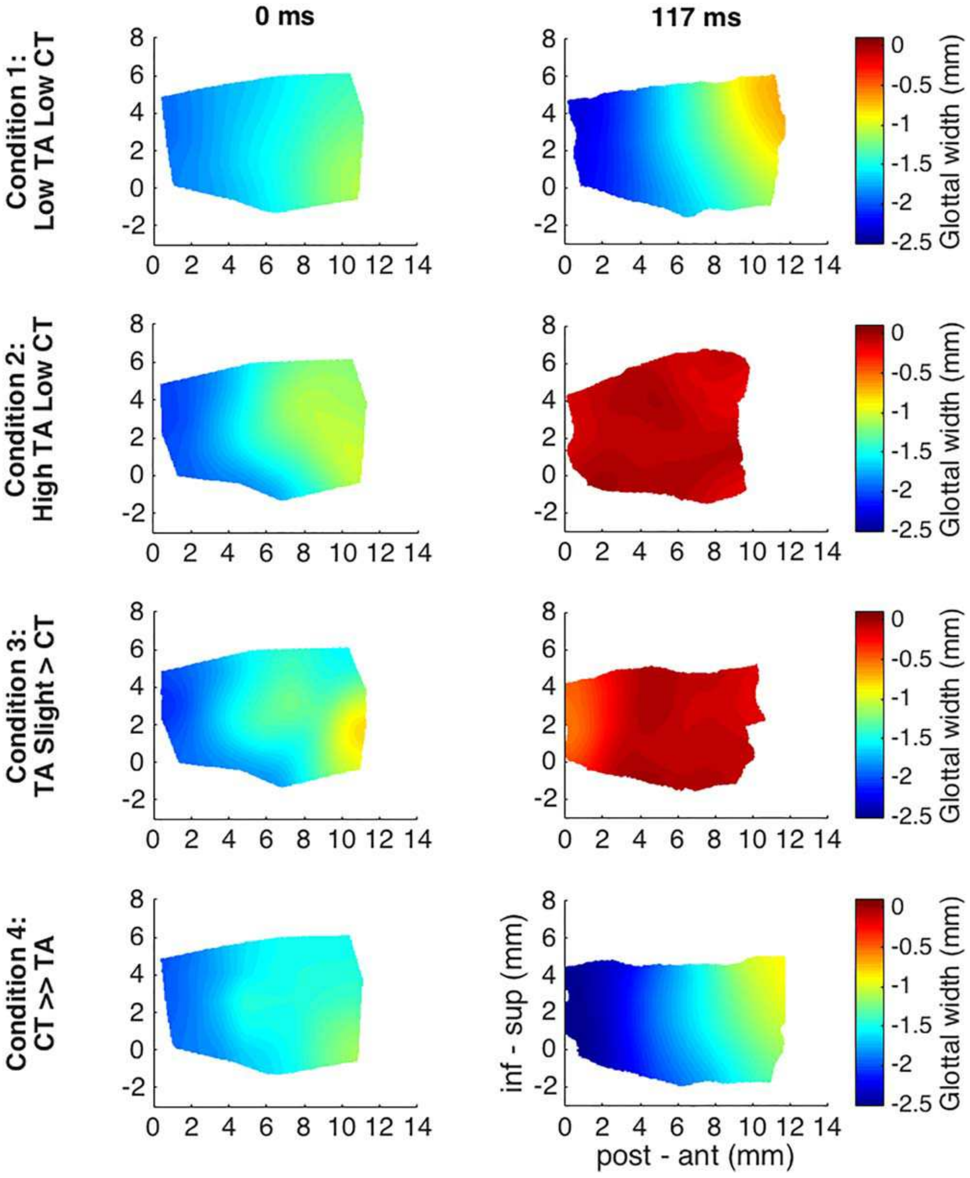

Fig. 3. Color-coded three-dimensional contour maps of the vocal fold surface for Hirano's four adjustments. The same representative combinations of TA and CT muscles (as in Fig. 2) were chosen for each of Hirano's four conditions. Color bar represents vocal fold glottal width, the distance of the vocal fold medial surface from the glottal midline (z dimension). The left column is the resting posture at 0 ms. The right column is the final activated posture at 117 ms following stimulation onset. Inferior-superior (inf-sup) shape change is shown in the y dimension. Posterior-anterior (post-ant) shape change is shown in the x dimension. Conditions 1 to 4 are presented on rows 1 to 4, respectively. Condition 1 appears to lengthen the vocal fold. Condition 2 shortens, thickens, and adducts the vocal fold. Condition 3 maintains or lengthens, thins, and adducts the vocal fold. Lastly, condition 4 lengthens and thins the vocal fold while slightly abducting. CT = cricothyroid; TA = thyroarytenoid. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

commissure (ant cord). Blue lines represent resting coronal posture, whereas red lines depict final posture 117 ms following stimulation. We chose this end time based on our prior work.[7,8] Here you see a slight favoring of a convergent glottis in condition 1, near complete vocal fold adduction in conditions 2 and 3, and slight abduction in condition 4. Overall, despite the unique coronal sections Hirano drew for each of his four conditions, we fail to appreciate much change amongst conditions beyond simple adduction and abduction. Importantly, conditions 2 and 3 must be interpreted with caution, as adduction ultimately leads to the vocal fold medial surface contacting the glass prism in the midline that will directly influence the coronal shape. However, the glass prism will function much like an endogenous contralateral vocal fold, and ultimately, this suggests that with robust vocal fold adduction the glottal channel assumes a rectangular configuration.

Our model also allows for 3D reconstruction of the entire medial surface contour. In Figure 3, we show the baseline medial surface contour plot (first column) and the final posture medial surface contour plot 117 ms after stimulation (second column) for these four conditions. There is subtle difference in the baseline contour for each condition, the absolute value of which is insignificant. These differences are a product of the software algorithm that must estimate the baseline contour plot each time a new condition is presented. For Low TA Low CT, we see lengthening of the vocal fold, maintained thickness, and minimal in-plane motion. For High TA Low CT, the vocal fold shortens, thickens, and adducts. For TA Slight > CT, the vocal fold length is maintained or increased, and the vocal fold is thinned and adducts. For CT >> TA, the vocal fold lengthens, thins, and abducts.

In Figure 4, we average the change in vocal fold length, anterior, and mid fold thickness, and vocal fold

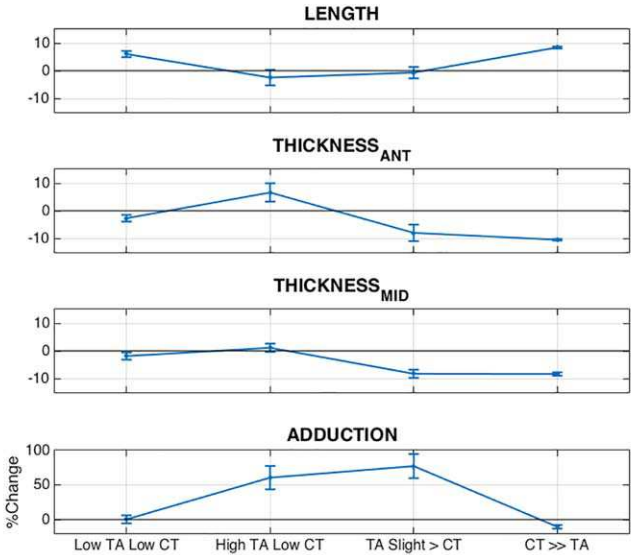

Fig. 4. Percentage change in vocal fold parameters for Hirano's four laryngeal adjustments. Each graph plots the average percentage change for a given parameter (i.e., vocal fold length, anterior fold thickness, mid fold thickness, and adduction) for each of the four laryngeal configurations. Condition 1, Low TA Low CT, includes TA and CT muscle activation levels 0 to 2 (n = 8). Condition 2, High TA Low CT, includes TA muscle activation levels 3 to 5 and CT muscle levels 0 to 2 (n = 8). Condition 3, TA muscle slightly greater activation than CT muscle (TA Slight > CT), includes TA and CT muscle levels 3 to 5 (n = 6). Lastly, condition 4, CT muscle activation much greater than TA muscle (CT >> TA), includes TA muscle levels 0 to 2 and CT muscle levels 3 to 5 (n = 7). Low TA Low CT lengthens the vocal fold by 6%, thins the anterior and mid fold by 2.7% and 1.9%, respectively, and provides near zero level of adduction. High TA Low CT shortens the vocal fold by 2.5%, thickens the anterior and mid fold by 6.6% and 1.1%, respectively, and adducts the vocal fold by 60.5%. TA muscle slightly greater than CT muscle does not impact length, thins the anterior and mid fold by 8.0% and 8.3%, respectively, and adducts the fold by 77.2%. Lastly, CT muscle much greater than TA muscle lengthens the vocal fold by 8.4%, thins the anterior and mid fold by 10.5% and 8.4%, respectively, and abducts the fold by 10.6%. Error bars = standard error of the mean. CT = cricothyroid; TA = thyroarytenoid; Thickness$_{\text{ANT}}$ = thickness of vocal fold medial surface 25% anterior to the mid fold; Thickness$_{\text{MID}}$ = thickness of the mid vocal fold medial surface. [Color figure can be viewed at www.laryngoscope.com.]

adduction for all combinations of the TA and CT muscles within Hirano's four paradigms. For Low TA Low CT, the vocal fold lengthens by 6%, thins by 2.7% and 1.9%, whereas adduction is relatively unaffected. For High TA Low CT, the vocal fold shortens by 2.5%, thickens by 6.6% and 1.1%, and adducts by 60.5%. For TA Slight > CT, the vocal fold length is unchanged, the vertical height thins by 8.0% and 8.3%, and adducts by 77.2%. Lastly, for CT >> TA, the vocal fold lengthens by 8.4%, thins by 10.5% and 8.4%, and abducts by 10.6%. Uniquely, for condition 2 and 3 (High TA Low CT and TA Slight > CT), the balance between TA and CT muscle activation leaves a relatively unchanged vocal fold length while adducting and thickening the fold in an isometric fashion. Overall, the glottal shape is uniquely altered for each of these four laryngeal conditions, with condition 1 lengthening, condition 2 thickening, condition 3 thinning, and condition 4 lengthening and thinning.

DISCUSSION

Hirano's G. Paul Moore Lecture in 1988 summarized 2 decades of his research.[2] The concept of the vocal fold with a cover and body layer having distinct loosely coupled mechanical properties was updated to include three distinct layers: the cover, including the epithelium and superficial layer of the lamina propria; a transition zone, including the vocal ligament; and the body, consisting of the vocalis muscle. Each layer has distinct mechanical properties with more pliability the more superficial the location.

Van den Berg was the first to discuss glottal shape as it relates to vocal registers.[11] In 1968, he showed coronal glottal schemes based on x-ray tomograms in a male larynx producing chest voice and a female larynx in falsetto. This alluded to vocal fold thickness as a key difference between chest and falsetto voice.[11] More recent work by Zhang using a 3D continuum model of phonation supported this finding.[12] Furthermore, chest voice is characterized by active longitudinal tensions in the vocalis muscle. Falsetto has thin vocal folds with passive longitudinal tensions in the vocal ligaments produced by the CT muscle.

Hirano's proposed four laryngeal conditions to explain the spectrum of vocal registers was a function of the ratio of vocalis to CT muscle activation. Current theories of register control hold that it is dependent upon intrinsic laryngeal muscle activity. Studies to date have observed changes in glottal shape indirectly through x-ray tomograms and videokymography. They have also used electromyography (EMG)to directly measure TA and CT muscle activity during various vocal exercises. In this report, we provide the first direct observation and quantitative analysis of prephonatory glottal shape under these four conditions using the canine hemilarynx model. In doing so, we see how the TA:CT ratio relates to vocal fold length, thickness, adduction, and medial surface contour.

The most developed analysis of the mechanisms of vocal registers have evaluated the activity of TA and CT muscles using laryngeal EMG. In the 1980s, Hirano published his work on laryngeal EMG to understand the role of laryngeal muscles in vocal register control.[2] Decades later, Kochis-Jennings et al. performed similar EMG work to understand the role of the TA and CT muscles in register control and the idea of muscle dominance. At low pitch, vocalists maintain or increase TA muscle activity as they transition to a heavier register. TA muscle activity is lowest for falsetto, low for head register, and greatest for higher pitch in the heavier registers. CT muscle activity was more variable between subjects.[2–4,13] These data corroborate Hirano's and Titze's grouping of CT/TA muscle activation into four conditions and supports our grouping of TA/CT muscle activation levels for analysis.

Activity of the TA muscle thickens the body of the vocal fold and slackens the cover. On videokymographic images of the vocal folds, these changes are reflected by increased sharpness of the lateral peaks in vibration patterns. Sharper lateral peaks suggest greater vertical phase difference, more activity of the TA muscle, and a thicker vocal fold. Such was seen by Herbst et al. for chest register in contrast to falsetto, suggesting adjustments in vocal fold thickness to achieve unique registers.[14–16] Here we directly appreciate the variation in vocal fold thickness as a function of register. We see increased vocal fold thickness for High TA Low CT, Hirano's second condition and Titze's pressed vocal register. For TA Slight > CT and CT >> TA, average vocal fold thickness decreases, and chest and falsetto registers are achieved, respectively.

Kochis-Jennings et al. also detail variations in vocal fold adduction across vocal registers. Most studies support that greater vocal process adduction occurs as singers move to heavier registers. Here we looked at adduction of the mid membranous vocal fold. Under conditions of TA and CT muscle activation that correspond to lighter registers, Hirano's condition 1 and 4, and Titze's speech/modal/falsetto register, vocal fold adduction is weak, absent, or opposite (abduction). Conversely, vocal fold adduction is strong for Hirano's condition 2 and 3, and Titze's pressed/chest registers.

Lastly, we provide a quantitative look at vocal fold length as it relates to vocal register and Hirano's four configurations. Vocal fold length is increased for light, speech, and falsetto registers (Hirano's condition 1 and 4) while unchanged for pressed and chest registers (Hirano's condition 2 and 3). In vocal register control, TA and CT muscles are antagonistic of one another. In this way, a near-isometric activation of the TA muscle is possible in heavier registers. Such fine tuning may help explain how singers can maintain a vocal register while altering pitch and vice versa.

Although our focus has been TA and CT muscle activity, surely the lateral cricoarytenoid (LCA) muscle also plays a part. Hirano's G. Paul Moore Lecture in 1988 demonstrates this clearly with LCA laryngeal EMG activity across different registers.[2] Here we chose to focus on TA and CT muscle activity to simplify activation combinations but plan to evaluate all three intrinsic laryngeal muscles in future work. It must also be noted that Hirano's original depiction of these four laryngeal adjustments were described as coronal sections during vocal fold vibration. Here, we do not incorporate vocal fold vibration or phonation. We are only interested in vocal fold prephonatory shape and the target to better modify and direct laryngeal framework surgery. In future work, we aim to incorporate vocal fold vibration and the resulting acoustics. We also aim to translate the canine hemilarynx model to a human ex vivo hemilarynx model, and in doing so, better understand unique and similar aspects of human laryngeal physiology to that of a canine.

The canine larynx is a well-accepted model of human laryngeal physiology. Histologically, anatomically, and geometrically the canine larynx does exhibit features distinct from human larynges. In canines, there is no vocal ligament as the elastic conus ends within the superficial lamina propria without forming a true ligament. The canine lamina propria is also thicker, contributing to its greater thickness, whereas the collagen and elastin densities are less concentrated.[17–19] Despite these differences, the function of the intrinsic laryngeal muscles is qualitatively the same. It has also been shown that similar glottographic waveforms can be achieved in canine and human larynges. Furthermore, the canine vocal folds generate similar vibration patterns to human vocal folds with mucosal waves and vertical phase differences, whereas the stiffness in the canine and human cover layers is no different.[2,18,20] In theory, these interspecies differences could explain our inability to appreciate a significant change in medial surface coronal contour. However, if so, we would expect prior studies to have found more functional differences between canine and human larynges. Nevertheless, translation of these techniques to the human ex vivo larynx will obviate such concerns. It should also be highlighted that the findings from this study are from a single canine experiment. We have repeated these experiments in two other canines that showed similar results. However, the canine presented in this study was the only one with the most complete dataset of all simulation conditions. As such, for simplicity and clarity we present the full dataset from this single canine.

CONCLUSION

Although the concept of vocal registers in part remains an enigma, Hirano's early work made great strides in conceptualizing the relationship between unique glottal configurations and vocal registers. The importance of glottal posture or shape on vocal registers is well recognized but poorly described. Here we provide a direct view of the vocal fold medial surface during each of Hirano's four paradigms. Low level TA and CT muscle lengthens the vocal fold, an excess of TA to CT muscle thickens and adducts the vocal fold, slight excess of TA to CT muscle thins and adducts the vocal fold, and a gross excess of CT to TA muscle lengthens, thins, and abducts the vocal fold. Meanwhile, the change in contour of coronal glottal sections is subtle.

BIBLIOGRAPHY

1. Hirano M. Morphological structure of the vocal cord as a vibrator and its variations. *Folia Phoniatr (Basel)* 1974;26:89–94.
2. Hirano M. Vocal mechanisms in singing: laryngological and phoniatric aspects. *J Voice* 1988;2:51–69.
3. Kochis-Jennings KA, Finnegan EM, Hoffman HT, Jaiswal S. Laryngeal muscle activity and vocal fold adduction during chest, chestmix, headmix, and head registers in females. *J Voice* 2012;26:182–193.
4. Kochis-Jennings KA, Finnegan EM, Hoffman HT, Jaiswal S, Hull D. Cricothyroid muscle and thyroarytenoid muscle dominance in vocal register control: preliminary results. *J Voice* 2014;28:652.e621–652.e629.
5. Chhetri DK, Neubauer J, Bergeron JL, Sofer E, Peng KA, Jamal N. Effects of asymmetric superior laryngeal nerve stimulation on glottic posture, acoustics, vibration. *Laryngoscope* 2013;123:3110–3116.
6. Chhetri DK, Neubauer J, Berry DA. Graded activation of the intrinsic laryngeal muscles for vocal fold posturing. *J Acoust Soc Am* 2010;127: El127-El133.
7. Vahabzadeh-Hagh AM, Zhang Z, Chhetri DK. Three-dimensional posture changes of the vocal fold from paired intrinsic laryngeal muscles. *Laryngoscope* 2017;127:656–664.
8. Vahabzadeh-Hagh AM, Zhang Z, Chhetri DK. Quantitative evaluation of the in vivo vocal fold medial surface shape. *J Voice* 2017;31:513.e515–513.e523.
9. Zhang Z, Neubauer J, Berry DA. Aerodynamically and acoustically driven modes of vibration in a physical model of the vocal folds. *J Acoust Soc Am* 2006;120(5 pt 1):2841–2849.

10. Titze IR. Principles of Voice Production. Iowa City, IA: National Center for Voice and Speech; 2000:281–303.
11. Van den Berg J. Register problems. *Ann N Y Acad Sci* 1968;155:129–134.
12. Zhang Z. Cause-effect relationship between vocal fold physiology and voice production in a three-dimensional phonation model. *J Acoust Soc Am* 2016;139:1493.
13. Hirano M. The laryngeal muscles in singing. In: Kirchner J, Bless D, eds. Neurolaryngology. Boston, MA: College Hill Press; 1987:209–230.
14. Herbst CT, Ternstrom S, Svec JG. Investigation of four distinct glottal configurations in classical singing—a pilot study. *J Acoust Soc Am* 2009; 125:El104- El109.
15. Svec JG, Sundberg J, Hertegard S. Three registers in an untrained female singer analyzed by videokymography, strobolaryngoscopy and sound spectrography. *J Acoust Soc Am* 2008;123:347–353.
16. Svec JG, Sram F, Schutte HK. Videokymography in voice disorders: what to look for? *Ann Otol Rhinol Laryngol* 2007;116:172–180.
17. Berke GS, Moore DM, Hantke DR, Hanson DG, Gerratt BR, Burstein F. Laryngeal modeling: theoretical, in vitro, in vivo. *Laryngoscope* 1987; 97(7 pt 1):871–881.
18. Garrett CG, Coleman JR, Reinisch L. Comparative histology and vibration of the vocal folds: implications for experimental studies in microlaryngeal surgery. *Laryngoscope* 2000;110(5 pt 1):814–824.
19. Sanders I, Rai S, Han Y, Biller HF. Human vocalis contains distinct superior and inferior subcompartments: possible candidates for the two masses of vocal fold vibration. *Ann Otol Rhinol Laryngol* 1998;107(10 pt 1):826–833.
20. Chhetri DK, Rafizadeh S. Young's modulus of canine vocal fold cover layers. *J Voice* 2014;28:406–410.