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Cricothyroid Joint Type as Predictor for Vocal Fold Elongation in Professional Singers

Claudio Storck, MD; Fabian Unteregger, MD

Objective: Vocal fold (VF) elongation vocal folds depends on two factors: the activity of the laryngeal muscles and the cricothyroid joint (CTJ). The aim of the study was to show the influence of the CTJ on VF elongation while singing a sustained vowel at different pitches.

Study Design: Prospective study.

Methods: Forty-nine female professional singers (25 sopranos, 24 altos) were recruited. Three-dimensional images of the larynx derived from high-resolution computed tomography scanning were obtained at the mean speaking fundamental frequency (F0) and one (F1) and two octaves (F2) above this pitch.

Results: From F0 to F1, all three CTJ types showed equal elongation of the VF (type A: 14%, type B/C: 13%). From F1 to F2, VF elongation was 8% in singers with type A and 4% in those with type B/C (P < 0.0001).

Conclusion: The stability of the CTJ directly influences VF during singing. This is the first study to show this relationship in vivo.

Key Words: Larynx, biomechanics, three-dimensional, 3D, singer, MIMICS, cricothyroid joint, vocal fold elongation.

Level of Evidence: 4.

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INTRODUCTION

The level of the vocal pitch can be influenced by the shape of the resonance space and the relative height of the larynx within the pharynx, as well as by specific vocal fold properties and adjustments that influence the frequency of vibration, such as stiffening, relaxation, and elongation. Our previous studies have shown that vocal pitch is first increased by elongation of the vocal fold through the cricothyroid muscle (CTM), which causes a backward tilting of the cricoid; and then by stretching of the vocal fold through the lateral cricoarytenoid muscle (LCAM), which leads to inferior displacement of the vocal process of the arytenoid cartilage.1,3–5

To our knowledge, this has not yet been analyzed in vivo; thus, we have specifically analyzed elongation and stretching of the vocal folds with regard to the cricoarytenoid joint (CTJ) type. The laryngeal muscles (CTM, thyroarytenoid muscle [TAM], lateral cricoarytenoid muscle [LCAM], and posterior cricoarytenoid muscle [PCAM]) change the position of the arytenoid cartilage and the vocal process. The extent of elongation of the vocal fold is not only dependent on the contraction of muscles but may also be influenced by the type of CTJ.1,3–5 This mechanism seems key. As with a musical string instrument, the tension and length of a string have a significant impact on the pitch. Given the foundation of physics, the vocal folds behave like a string of an instrument. In contrast to an instrument in which various pitches are achieved by various strings, the human voice only has one (parallel) string: the vocal folds. Here, the modulation of the pitch happens by altering its properties such as stiffening, relaxation, and elongation.

In order to elongate and stretch the vocal folds, the laryngeal muscles (TAM, LCAM, CTM, and PCAM) change the position of the arytenoid cartilage and the vocal process. Nevertheless, the extent of elongation of the vocal fold is not only dependent on the contraction of muscles but also on the type of CTJ.1,3–5

The CTJ is not a uniform anatomical entity. In 1971, Maue and Dickson5 published a study based on dissection of larynges from human cadavers wherein they concluded that the CTJ comes in three different anatomical variants: 1) type A, defined as a joint with a concave central area and facets on a protuberance with a strong capsule; 2) type B, characterized by a flat surface on the cricoidal part of the joint, with a cartilaginous joint facet and loose capsular tissue; and 3) type C, characterized by a flat surface on the cricoidal joint, without a visible joint facet and loose capsular connective tissue. Apart from a description of the three joint types, Maue and Dickson5 did not further analyze them in a clinical or other context.

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In another cadaver study, Hammer et al. showed that the difference in joint mobility, especially between type A and the two other types (B and C), was highly significant. According to these authors, well-defined facets seem to enable mobility. Windisch et al. came to similar conclusions and furthermore stated that the type A CTJ occurred in 61% of their analyzed cadaver larynges, type B in 22%, and type C in 17%. With regard to joint mobility, Vilkman et al. showed in the framework of another cadaver study that ventrodorsal gliding was possible when the joint was not rotated to its extremes. Moreover, they concluded that although gender had little impact on the extent and way the gliding takes place on the joint facets of the CTJ, the higher the collagen content of both the joint capsule and surrounding ligaments, the less gliding was possible.

Based on three-dimensional (3D) images of cadaveric larynges, Storck et al. demonstrated the effect of CTJ type on the extent of elongation of the vocal fold. The elongation measured 12% in type A, 8% in type B, and 4% in type C. Based on these observations, Tschan et al. analyzed the extent of elongation after cricothyroid approximation in gender dysphoria (transwomen). In their study, a significant relationship between elongation and CTJ type could be demonstrated, and a correlation between CTJ type and voice pitch elevation was observed. Later, in a pilot study on professional singers, Vorik et al. showed the same relationship between CTJ type and elongation of the vocal fold, namely that type A CTJs are related to greater elongation and vocal pitch elevation.

In a recent study of 48 singers, Unteregger showed that, regardless of CTJ type, elongation and tensioning of the vocal folds from the mean speaking fundamental frequency (F0) to the first octave (F1) occur by CTM activation, and that from the first to second octave (F2), elongation and tensioning occur by activation of both the LCAM and TAM. At first glance, these results are in contrast with the cadaver studies. Therefore, the aim of this study was 1) to analyze the course of vocal fold elongation during singing over two octaves, 2) determine how the CTJ influences vocal fold elongation in vivo, and 3) prove the results of recent studies regarding whether the elongation observed in imagery can also be found in a physiologically functioning larynx.

The aim of this study is to specifically assess the impact of CTJ type on vocal fold elongation in order to deepen the understanding of both the laryngeal biomechanics and laryngeal functionality. In the current work, we used 3D imaging of the laryngeal cartilages (N = 49) derived from high-resolution computed tomography (HRCT) scans obtained while a vowel was sung (most frequently an /a/), a noninvasive technique that we previously used successfully in studies of various aspects of laryngeal biomechanics. Based on the scans, we assessed both the position and movement of the laryngeal cartilages. Because vocal folds are attached to the thyroid and the arytenoid (sitting on the cricoid), we assessed elongation of the vocal folds. Based on the position of the thyroid, cricoid plate, and arytenoid, in the current work we developed a model that shows how CTJ mechanics and muscle activation differ in the type A, B, and C joints in vivo.

PATIENTS AND METHODS

Study Population

Forty-nine female professional singers (25 sopranos and 24 altos) were recruited for this laryngeal study. The HRCT scans were part of all the information that we collected. All singers were active members of a professional vocal ensemble or were soloists. Of the 49 singers, 25 were sopranos and 24 were altos. All were active either as soloists or members of a professional vocal ensemble. The mean age for the sopranos was 44 (range 29–69) years, and the mean age for the altos was 39 (range 28–62) years. None of the singers reported having had any voice-related problems in the past 5 years. All singers said that they used two different mechanisms for pitch control, one for the lower range (M1) and one for the upper range (M2). The singers were asked at which pitch they usually changed registers from M1 to M2 and to state the highest note that they could sing in M1. Exclusion criteria were pregnancy (because they had to undergo HRCT), a Singing Voice Handicap Index of more than 17 points, or hidden laryngeal pathologies revealed by videolaryngostroboscopy.

This study was approved by the Medical Ethics Committee of Zurich (Switzerland).

High-Resolution Computed Tomography Imaging

All participants were asked to sing an open Italian /a/ (as in “Caro mio ben” by Giuseppe Giordani) at a comfortable mezzo-forte level and keep this level in mind. In absolute figures, this level varied between 75 and 85 dB. Rather than prescribe a fixed loudness, we preferred that each singer determine her own comfortable loudness. We assumed that this approach would facilitate maintaining the same loudness throughout the exam. Each singer then underwent three HRCT scans. To assess the extent of the lower range (M1), all the singers sang the highest possible /a/ in the lower range. They also sang the same /a/ at the frequency at which they switched into the upper range (M2). All singers sang separately the /a/ at the same loudness at the mean speaking fundamental frequency F0 (calculated using DIVAS software, XION Medical, Berlin, Germany), one octave (F1), and finally two octaves (F2) above F0.

Because the study focused on the impact of CTJ type on vocal fold elongation, frequency dependency was not observed. All singers were able to sing F0, F1, and F2. Scans were begun 2 cm below the glottis, with the first scan going up to the hard palate and the second and third scans only as far as the superior horn of the thyroid. The first scan went higher because it was also used for further studies.

A clinical multislice CT scanner (Siemens Definition AS 64, Siemens Healthcare, Erlangen, Germany) was used with the following settings: slice thickness = 1 mm, pitch = 0.8, increment = 1 mm, rotation time = 1 second, and maximal voltage and tube current = 120 kVp and 150 mA (total radiation dosage for all three scans: 2.1 mSv). The scans were performed using a high-resolution technique with the participant in the supine position. The image acquisition time was 10 to 12 seconds for the first scan and 7 to 9 seconds each for second and third scans. No singer experienced any difficulty maintaining a steady tone for this time.
**Postprocess Imaging**

After assessing the HRCT, the Digital Imaging and Communications in Medicine data were postprocessed with the segmentation software MIMICS (version 14.0, Materialise, Leuven, Belgium).13 The HRCT scans were first segmented into cartilages and then transformed into 3D models.12 To analyze the motion of the ecrioid cartilage and the arytenoid cartilages during singing, we superimposed the 3D images of the three acquisitions obtained at F0, F1, and F2. By superimposition of the three images (F0, F1, F2), we could analyze the elongation independently of the position of the larynx within the neck. To calculate vocal fold length, we defined the anterior commissure and the vocal process of the arytenoid cartilage in the 3D images at F0, F1, and F2 as landmarks. MIMICS (Materialise) was then used to calculate the distances between them. For the statistical analysis of the results, we used the analysis of variance and the Wilcoxon rank sum test for equal medians.

**RESULTS**

**Visualization and Three-Dimensional Rendering of Laryngeal Cartilages and Cricothyroid Joint Type**

Initially, all laryngeal cartilage skeletons were segmented. In all scans, the laryngeal cartilages (i.e., cricoid plate, thyroid, and arytenoids) could be visualized and rendered three dimensionally; moreover, all CTJs could be visualized. The corresponding 3D images obtained at F0, F1, and F2 could be superposed. A total of 27 out of 49 (55%) larynges showed a type A CTJ, with the typical protuberance and concave central area. The remaining 20 (43%) larynges showed a flat joint surface. As mentioned by Tschan et al.,3 it was impossible to assess whether these non-A type joints had a minimal cartilaginous joint facet (type B) or did not have one (type C). Therefore, the distinction between type B and type C based on our 3D images was not possible. We thus will refer to subjects as having either type A or type B/C joints. Of the 29 A type CTJs, 12 (41%) were sopranos and 17 (59%) were altos. Of the 20 B/C type CTJs, 13 (65%) were sopranos and seven (35%) were altos. There was no significant difference between alto and soprano. Furthermore, no correlations were found between vocal registers and CTJ types. Sopranos did not have a greater voice compass; they just started at a higher pitch.

**Elongation of Vocal Folds: Type A Versus Types B and C**

In the type A CTJ, the average vocal fold length was 17.9 mm in F0 (range, 14.0 mm–20.3 mm), 20.4 mm in F1 (range, 16.1 mm–23.0 mm), and 22.0 mm in F2 (range, 18.4 mm–25.3 mm). The elongation of the vocal folds increased by 14% from F0 to F1 and by 8% from F1 to F2 (Table I). The total elongation from F0 to F2 increased by 22%.

In type B/C CTJ, the average vocal fold length was 17.9 mm in F0 (range, 16.1 mm–22.3 mm), 20.2 mm in F1 (range, 17.7 mm–25.4 mm), and 21.0 mm in F2 (range, 18.9 mm–27.8 mm). Elongation of the vocal folds increased by 13% from F0 to F1 and by 4% from F1 to F2. The total elongation from F0 to F2 was 17% (Table I).
study, we confirmed the findings of Vorik et al. CTJ type dependency could thus be confirmed. In this approximation surgery. The assumption of vocal pitch women) patients could be treated with cricothyroid voice of around two-thirds of gender dysphoria (trans-

Fig. 1. Comparison of the elongation of the vocal folds of the different cricothyroid joints.
*P < 0.0001 for the paired t test.
†P < 0.0001 for the unpaired t test.
CI = confidence interval.

first time show this in a small group (N = 10) in a pilot study on professional singers.¹

In a recent study, we showed the motion sequence of laryngeal cartilage during singing a sustained vowel over two octaves.² Within the first octave in which M1 is employed, the CTM is active. Within the second octave in which M2 is in use, both LCAM and TAM are active. In this study, we report two findings:

1. We confirm the findings of the preceding studies as well as the pilot study. There is a significant relationship between CTJ type and elongation of the vocal folds.

2. Independent of CTJ type, vocal fold elongation does not occur in a linear manner over two octaves with these tasks.

However, in one study showing direct connection between CTJ type and vocal fold elongation, threads were pulled in a trial to simulate the effects of the CTM. Although we tried to simulate the CTM as ideally as possible, there was an iatrogenic bias. Therefore, an in vivo connection could not be confirmed.

Whereas Maue and Dickson⁵ described the three CTJ types, Windisch et al.⁷ found that roughly 60% of people have the type A. Tschan et al.³ found that the voice of around two-thirds of gender dysphoria (trans-women) patients could be treated with cricothyroid approximation surgery. The assumption of vocal pitch CTJ type dependency could thus be confirmed. In this study, we confirmed the findings of Vorik et al.¹ pilot study. The type A CTJ yields a vocal fold elongation of 23%, whereas the B/C type only reaches 18%. This difference is highly significant.

Looking at our results from a voice category, 12 (41%) of the 29 type A CTJs were sopranos and 17 (59%) were altos. In the group of the 20 type B/C CTJs, 13 (65%) were sopranos and seven (35%) were altos. Neither a significant difference nor a correlation between vocal registers and CTJ types was found. In contrast to the widespread opinion, sopranos did not have a greater voice compass; they just started at a higher pitch. This could, however, be biased by the fact that we have analyzed a professional group of singers. Therein, even singers with a B/C CTJ may have developed techniques to overcome the disadvantage of a larynx with a CTJ that cannot substantially elongate its vocal folds.

Vocal fold elongation occurred in a nonlinear manner over two octaves irrespective of CTJ type. As shown in Table I, all three CTJ types enable an almost identical elongation in the first octave of 14% in type A and 13% in type B/C, whereas in the second octave, type A elongates 8% and type B/C elongates only 4%. Over all types, there is much less elongation occurring in the second octave in comparison to the first. Therefore we need to answer two questions: First, how can the differences in elongation in the first and second octave be explained? Second, how can the significant difference in elongation in the second octave between types A and B/C be explained?

To address the first question, Unteregger et al.² showed that the cricoid tilts 85% of its maximum possible amount during the first octave, whereas a further 15% of the tilting occurs in the second octave. Therefore, vocal fold elongation also occurs through CTM activation in the second octave. This is also supported by the claim by Unteregger et al. that the examined singers were able to sing a further two to three half-tones using mechanism M1 without having to switch to mechanism M2. These findings are in line with Hirano,¹⁶ who showed that the CTM is active in the second octave as well. However, Unteregger et al.² showed that there is another mechanism involved during the second octave. Motion of the arytenoid cartilages could be observed. Within M2 (second octave), they tilt inward and rotate backward, both due to a LCAM contraction. The vocal process thereby moves from the top laterally to downward medially and posteriorly, which again leads to further vocal fold elongation. Hence, in the second octave, vocal fold elongation is the sum of both CTM and LCAM activity. Finally, it is impossible to calculate the amount of elongation that each muscle contributes.

To address the second question, as we mentioned above, the CTM is responsible for the first octave (F0–F1). In an EMG study, Hirano¹⁶ demonstrated that the CTM is still active at high pitches. This is comparable to our recent study.² At higher pitches, the CTM stabilizes the cricoid in the backward tilted position versus the thyroid. Therefore, we believe that the solution to this significant difference in vocal fold elongation lies in CTJ type. Both type A and type B/C achieve the same vocal fold elongation in the first octave (F0–F1) (Fig. 2, images 1, 2 and 5, 6).

With the type A CTJ, elongation in the second octave is a product of the LCAM. The LCAM contraction leads to an inward rotation and rocking of the two arytenoid cartilages such that the two vocal processes will move posteriorly and downward. This motion results in an elongation of the vocal fold. The TAM, as its name implies, sits in between the thyroid and the arytenoids and stiffens the vocal fold. In the proper sense, the TAM
contraction causes the thyroid cartilage to approach the arytenoid cartilage. Due to the stable capsule of the CTJ, a backward shift of the thyroid toward the arytenoids is impossible (Fig. 2, images 3 and 4). Therefore, the elongation is the direct result of the contraction of the LCAM.

In type B/C CTJ, however, the LCAM contraction leads to an additional inward rotation and rocking of the arytenoid cartilage, with an elongation of the vocal fold. Yet, with this joint type the TAM not only stiffens the vocal fold, as mentioned above, with loose connective tissue as a joint capsule compared to type A with a tight capsule, but probably also leads to a backward shift of the thyroid toward the arytenoid cartilages. Therefore, the vocal fold elongation of the LCAM is reduced by an approximation of the thyroid toward the two arytenoid cartilages (Fig. 2, images 7 and 8).

Our study has five limitations. First, we have assessed the elongation of the vocal folds independent of the three CTJ types while singing a sustained vowel. Our finding thus might not be applicable to singing glissandos and functional singing tasks. Second, we included only women. Third, the women were all professional singers. Fourth, we did not assess the impact of the extra laryngeal muscles. Fifth, the minimal shift of the thyroid cartilage in type B/C CTJs is not visible.

CONCLUSION
This is the first study showing the biomechanical effect of the CTJ in vivo. Our results suggest that CTJ type probably also influences the vocal range. This remains to be proven in a further study.

BIBLIOGRAPHY


