Acoustic Research Letters Online

JULY 01 2005

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ARLO 6, 112–117 (2005)
https://doi.org/10.1121/1.1899723

Review of range of arytenoid cartilage motion

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Abstract: Vocal fold abduction/adduction posturing is key to phonation control. As biomechanical models of the larynx increase in complexity, there is a need to verify them with laboratory data. To help experimental cross-validation of models, ranges of vocal process displacement were reviewed and combined. Although general inter-study agreement was found, there was substantial variation. Using a model of vocal fold posturing, insights were uncovered that could not otherwise be made; best-practice guidelines and research avenues for future studies of vocal posturing were also outlined.

PACS numbers: 43.70.Bk, 43.70.Aj
Date Received: May 13, 2004 **Date Accepted:** April 12, 2005

1. Introduction

Hunter and Hunter[1] discussed the need for a compiled knowledge base of arytenoid motion to: (1) consolidate data in one location, helping to clarify the current understanding of cricoarytenoid joint (CAJ) mechanisms; (2) improve future studies by highlighting similarities/differences in methodology and resulting measures; (3) verify biomechanical models of vocal-fold posturing and to improve surgical/therapeutic techniques; and (4) draw attention to seemingly unintuitive observations, which could then be explored through further laboratory studies or through biomechanical models. To address this need, the goal of this review is to compile known arytenoid cartilage motion ranges in terms of vocal process displacement. In addition, posturing was simulated with a biomechanical model of the larynx to contribute to the understanding the review.

Five papers[2–6] reporting measures of ranges from laboratory experiments were found to discuss arytenoid motion using a landmark that was equivalent to the vocal process. For several of these studies, it was necessary to calculate arytenoid cartilage motion from the data given in terms of the vocal process (the true anatomical vocal process at the tip of the arytenoid, VP_T; or the medial vocal-fold edge near the vocal process, VP_M). Studies of arytenoid motion that did not use the vocal process as a landmark, or did not provide enough information for their results to be related to the vocal process, were excluded from this review (examples include Refs. 7–9). Motion of the vocal process was described with respect to the cricoid cartilage, as shown in Fig. 1 (x: medio-lateral, rightward positive; y: anterio-posterior, anterior or frontward positive; z: inferio-superior, superior or upward positive). Figure 2 illustrates the relation of the arytenoid to the cricoid, with the approximate position of the vocal process labeled as VP.

2. Review

Kotby *et al.*[4] studied the gross displacement of the vocal-fold edge during abductory/adductory motion (simulated by placing tension on sutures attached to the arytenoid). Using 14 fresh adult human larynges (eight male, six female), the displacement in the coronal plane (left–right and up–down) was tracked at three points along the vocal-fold length (middle, 4-mm anterior, and 4-mm posterior); Kotby's posterior point was assumed from the description (though not directly

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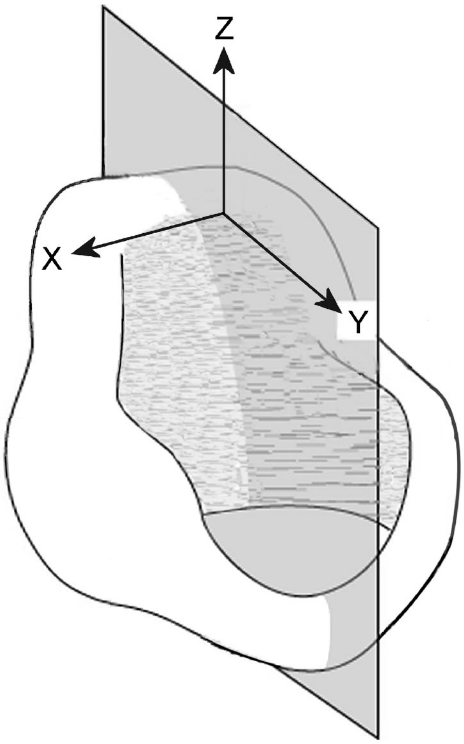

Fig. 1. Coordinate system from the vantage point of the cricoid cartilage (after Selbie *et al.*.)

specified in the paper) to be near the vocal process position if projected to the medial edge (VP_M). Total x- and z displacements of VP_M could then be calculated from Kotby's data.

By attaching tensioned sutures to the arytenoid in a study of 20 excised human larynges (ten male, ten female), Hirano *et al.*[3] measured simulated glottic shaping of vocal posturing motion of abduction (primarily caused by the posterior cricoarytenoid, PCA) and adduction (caused by a combination of lateral criocoarytenoid, LCA, and thyroarytenoid, TA).

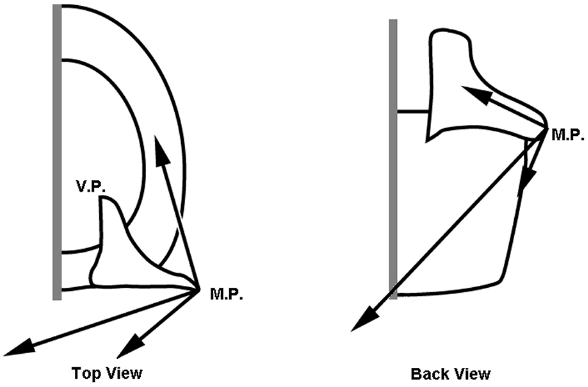

Fig. 2. The right half of the cricoid and the right arytenoid. Arrows represent the approximate direction of the LCA, PCA and IA which attach around the muscular process (M.P.). The vocal process, near the attachment of the vocal ligament and TA muscle, is also labeled (V.P.).

1529-7853/05/6(3)/113/6/$22.50

Table. 1. Vocal process displacement from each study. Total coronal displacement is the motion projected on the coronal plane. Total transverse displacement is total displacement projected on the transverse plane (as if looking from the top—an endoscopic-like view).

		Landmark	Δx (mm)	Δy (mm)	Δz (mm)	Coronal (mm)	Transverse (mm)	Total 3D (mm)	Number
Kotby	Total displacement	$\mathrm{VP_M}$	**5.2**	···	**2.0**	**5.5**	···	···	**14**
Hirano	PCA	$\mathrm{VP_M}$	2.6	0.4	···	···	···	···	**20**
	LCA+TA		−2.2	−1.1	···	···	···	···	
	Total displacement		**4.8** (±1.3)	**1.5** (±0.3)	···	···	**5.1**	···	
Woodson	Arytenoid adduction procedure	$\mathrm{VP_M}$	···	···	**2.6**	···	···	···	**3**
Wang	**Total displacement**	$\mathrm{VP_T}$	**5.2** (±1.0)	**0.3** (±0.8)	**1.9** (±0.7)	**5.5**	**5.2**	**5.5**	**7**
Frable	Relative measure	$\mathrm{VP_T}$	$2 \cdot y$	···	···	···	···	···	**10**
Simulation	PCA	$\mathrm{VP_M}$	2.1	0.4	0.8	···	···	**2.2**	
	LCA		−1.0	−0.6	−1.9	···	···	**2.2**	
	IA		0.3	−0.1	1.2	···	···	**1.3**	
	TAM		−0.7	−0.3	−1.2	···	···	**1.4**	
	TAV		−0.2	−0.1	−0.3	···	···	**0.4**	
	Total displacement		**3.1**	**1.0**	**3.1**	**4.4**	**4.3**	**4.5**	
Simulation	PCA	$\mathrm{VP_T}$	1.7	−0.2	0.5	···	···	**1.8**	
	LCA		−1.2	−0.2	−1.6	···	···	**2.0**	
	IA		0.5	0.0	1.0	···	···	**1.1**	
	TAM		−0.8	−0.1	−1.0	···	···	**1.3**	
	TAV		0.1	0.0	−0.3	···	···	**0.3**	
	Total displacement		**2.9**	**0.2**	**2.6**	**3.9**	**2.9**	**3.9**	

These measures (e.g., glottal width, anterior length, and membranous length) were made in the transverse plane only. The maximum range of the $\mathrm{VP_M}$ in the x- and y directions, although not provided in the study results, could be calculated from a combination of provided measures.

Wang[5] used fluoroscopic imaging and recording to capture the motion of the $\mathrm{VP_T}$ and muscular process in seven excised human larynges (three male, four female) from top, side, and front views. As the arytenoid was manipulated from full adduction to full abduction, the landmark paths were captured and the entire three-dimensional range was recorded and averaged. In addition, by methodically disconnecting individual tissue attached to the arytenoid, Wang inferred the contribution of CAJ motion from muscles and ligaments. Full three-dimensional ranges from the displacement paths of the $\mathrm{VP_T}$ were compiled.

Two additional studies provided limited, albeit important, information. In one of the classic studies that helped to redefine how arytenoid motion was conceptualized, Frable[2] studied ten fresh human larynges in an effort to define the joint axis of the CAJ. Her report found that left–right displacement of the $\mathrm{VP_T}$ is about two times greater than front–back (written in Table I as $x=2y$). Second, Woodson *et al.*[6] used three excised human larynges to study vertical positions of the VP_M during various arytenoid adduction procedures. They found that the vocal process could be vertically displaced 2.6 mm from cadaveric position.

Range of vocal process motion was simulated using the Hunter *et al.* vocal posturing model.[10,11] Hunter's model used the full activation of the four intrinsic laryngeal muscles attached to the arytenoid (contracted in isolation, see Mm. 1–5), or the PCA, LCA, interarytenoid (IA), and TA muscles (the two major bellies of the TA were treated as two separate muscles, the thyromuscularis, TA_M, and thyrovocalis, TA_V). The model was three-dimensional and included deformation of vocal-fold tissues.

Mm 1. Vocal-fold model dynamics of a PCA-only contraction.

Mm 2. Vocal-fold model dynamics of an LCA-only contraction.

Mm 3. Vocal-fold model dynamics of an IA-only contraction.

Mm 4. Vocal-fold model dynamics of a TA_M-only contraction.

Mm 5. Vocal-fold model dynamics of a TA_V-only contraction.

Higher resolution versions can be found at: http://www.ncvs.org/ncvs/library/tech/

Hunter's model could predict not only the VP_T position, but also the VP_M position (which would vary with bulging), approximately 0.7 mm apart medio-laterally. Details of the model, as well as a multimedia elongation/contraction of one muscle in isolation (simulating a free, dissected muscle and illustrating the model's interior workings) can be found elsewhere.[10]

3. Results and discussion

Table I contains the compiled results of all reviewed studies, as well as the modeled results of Hunter *et al.* All measures are in terms of the displacement of the respective vocal process landmark; also listed are total coronal, transverse (endoscopic-like view), and three-dimensional displacement. Wang reported the most comprehensive examination of vocal process range of motion, while the Hirano *et al.* study gave the most comprehensive look at glottal shaping and potential muscle contributions. The most complete measure was the Δx, which was comparable to abductory/adductory glottal width. The Hunter model generally underestimated the total ranges seen in the papers reviewed.

Because Wang furnished the most complete data set of the vocal process range of motion, including the only reported three-dimensional extent of vocal process movement (5.5 mm), these measures become an important base for comparing the remaining data from the reviewed papers and the model. Using VP_M, Kotby *et al.* showed the same Δx as Wang (who used VP_T). Further, Hirano *et al.* (who also used VP_M) reported a similar Δx (4.8 vs 5.2 mm); however, Hirano *et al.* saw a total Δy of 1.5 mm, while Wang only observed 0.3 mm. The Hunter model, which was capable of tracking both vocal process landmarks, points to the choice of landmarks as the reason for this discrepancy. Like the respective measures taken by Hirano *et al.* and Wang, the Hunter model predicted that the two different vocal process landmarks would result in similar Δx (3.1 vs 2.9 mm), but distinct Δy (1.0 vs 0.2 mm). Therefore, the model's confirmation of laboratory measures suggests that Δx is less dependent on vocal process landmark choice than Δy.

Discussion of Δz is less conclusive. Although both used VP_M, Kotby *et al.* varied considerably from Woodson *et al.*; nevertheless, both measures were greater than that seen by Wang (using VP_T). However, because the standard deviation of Wang was large enough to include the two distinct measures of Kotby *et al.* and Woodson *et al.*, no conclusions could be drawn directly from the laboratory data. However, the predictions of the Hunter model suggest there is a greater Δz using VP_M than VP_T, an insight that is supported, but not proven, by the laboratory data. A second conclusion that was drawn from these data was that like Δx, Δz might not be as dependent on the landmark choice as Δy. However, the variation in the measures could not confirm either conclusion.

Of all the reviewed studies, only Hirano *et al.* presented muscle-specific ranges of the vocal process, albeit simulated with a suture at the discretion of the experimenter. Using the same landmark, Hunter's model generally agreed with Hirano's measured value for PCA-caused vocal process displacement (Δx, 2.6 vs 2.1 mm; Δy, 0.4 vs 0.4 mm). Hirano's combined LCA-TA measure resulted in −2.2 mm Δx and −1.1 mm Δy. Hunter's model agreed with Hirano's directions of the motion for all individual TA and LCA contributions; however, since the LCA and TA were not contracted in combination in the model, the resulting summed magnitude may not be comparable (even though the individual results approximate the standard deviation of Hirano's measures).

In general, Hirano *et al.*, Kotby *et al.*, and Wang agreed within the standard deviation (as measured by Wang) for Δx. The Δz for Woodson *et al.*, Kotby *et al.*, and Wang were also within Wang's standard deviation. However, it is crucial to note that the standard deviation for each displacement was a significant percentage of the overall range: approximately 20% of the overall Δx, and 35% of the overall Δz. Thus, with the variation such a large percentage of the mean, the data's usefulness is somewhat limited unless the variations were related to a specific cause.

It seems logical that these reported variations would be caused primarily by intersubject variation in overall laryngeal size (e.g., a large larynx would have a large range of motion). Nevertheless, if these variations in ranges were dependent on size alone, the variations would be proportional to the variations in cartilage size. However, the percentage of variation in size across adult larynges (11%–15% for thyroid cartilage anterio-posterior length and width at the level of the vocal fold[12]) is much less than the percentage of variation in range of motion (20%–35%, as reported above). Although it is still possible that some of these variations were indeed caused in part by variations in size across larynges, the studies' methodologies (and resulting data) do not answer categorically to what degree standard deviations this large were caused by interspecimen variations or methodological differences (or a combination of both factors).

4. Conclusions

This review begins the process of compiling a knowledge base of arytenoid motion. A key insight from the current review suggested that the two common definitions of the vocal process (the true anatomical vocal process at the tip of the arytenoid, and the medial vocal-fold edge near the vocal process) could produce variations in range of motion. The anterior–posterior range of the vocal process appeared to be most dependent on the choice of vocal process landmarks (as compared to the medio-lateral and superior-inferior ranges). In contrast, the medio-lateral range appeared to be almost independent of vocal process landmark choice; this fact could be particularly important given that most clinical studies of vocal posturing use glottal width (as measured by the medio-lateral distance between the vocal folds), or an equivalent to it, as their primary metric.

A primary conclusion that can be drawn from the current review is the need for best-practice guidelines for future studies exploring the cricoarytenoid joint. First, it is crucial that studies unambiguously report subject characteristics and study methodology, not only to increase dependability of studies, but also to enable interstudy comparisons. For example, future work measuring vocal process range of motion should detail subject characteristics like overall laryngeal size, making it possible to determine the effect of subject differences versus methodological differences on variations in results.

An additional best-practice guideline highlighted by the current study is the need for standard, unambiguous methodology, particularly with regard to landmark choice (e.g., mid-membranous vocal fold, CAJ axis point, or vocal process). To promote interstudy comparisons, it is suggested that the vocal process should be used as at least one of the primary landmarks. Further, studies should describe in detail all landmarks used and the specific method by which they were chosen; in the current review, many studies could not be included because they did not report the landmark used or provide a correlate in order to relate results of one study to another. Moreover, although the choice of landmark position is not usually considered a crucial aspect of laryngeal research, this review also suggests (as noted above) that even slight variations in landmark definitions may produce critical discrepancies in certain measures. Thus, it is recommended that, when using the vocal process, future studies identify and use one of two vocal process landmarks: the true anatomical vocal process at the tip of the arytenoid; or the medial vocal-fold edge near the vocal process.

In conclusion, as computational power increases, it will be possible to create more complex and realistic posturing models for biomedical purposes, such as the prediction of vocal injury or the simulation of phonosurgical outcomes. However, because posturing models must be able to simulate known measures, a knowledge base of vocal process range and speed is key to this endeavor. For this knowledge base to be usable, it is crucial that future studies resolve the issues behind the large variations in range of motion. Without this resolution, clinicians, phonosurgeons, and vocal researchers must continue to speculate on what is the normal range for a particular larynx.

Acknowledgments

This work is part of a research program entitled, "A Computational Tool for Simulation of Phonosurgical Procedures," supported by NIDCD Grant DC006801 from the National Institutes of Health. Thanks to Laura M. Hunter for the technical review.

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