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Spatial Motion of Arytenoid Cartilage Using Dynamic Computed Tomography Combined with Euler Angles

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Objective: To investigate the feasibility of dynamic computed tomography in recording and describing the spatial motion characteristics of the arytenoid cartilage.

Methods: Dynamic computed tomography recorded the real-time motion trajectory of the arytenoid cartilage during inspiration and phonation. A stationary coordinate system was established with the cricoid cartilage as a reference and a motion coordinate system was established using the movement of the arytenoid cartilage. The Euler angles of the arytenoid cartilage movement were calculated by transformation of the two coordinate systems, and the spatial motion characteristics of the arytenoid cartilage were quantitatively studied.

Results: Displacement of the cricoid cartilage was primarily inferior during inspiration. During phonation, the displacement was mainly superior. When the glottis closed, the superior displacement was about 5–8 mm within 0.56 s. During inspiration, the arytenoid cartilage was displaced superiorly approximately 1–2 mm each 0.56 s. The rotation angle was subtle with slight rotation around the XYZ axis, with a range of 5–10 degrees. During phonation, the displacement of the arytenoid cartilage was mainly inferior (about 4–6 mm), anterior (about 2–4 mm) and medial (about 1–2 mm). The motion of the arytenoid cartilage mainly consisted of medial rolling, and there was an alternating movement of anterior-posterior tilting. The arytenoid cartilage rolled medially (about 20–40 degrees within 0.56 s), accompanied by anterior-posterior tilting (about 15–20 degrees within 0.56 s).

Conclusion: Dynamic computed tomography recordings of arytenoid cartilage movement can be combined with Euler transformations as a tool to study the spatial characteristics of laryngeal structures during phonation.

Key Words: Dynamic CT, Euler angle, arytenoid cartilage, spatial motion.
Level of Evidence: 4

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INTRODUCTION

Studying the three-dimensional (3D) dynamic movement of larynx is very valuable for diagnosing vocal fold dyskinesia diseases, but how to describe the 3D movement of the larynx is challenging using typical methods for instrumental evaluation of the larynx, such as stroboscopic laryngoscopy and computed tomography (CT) imaging. These instruments do not describe the movement of laryngeal structures during phonation with a degree of resolution that allows for detailed analysis. Furthermore, calibration of the range of motion of the arytenoid cartilage is cumbersome due to its complex motion on several planes. Ideally, the motion of laryngeal structures such as the arytenoid cartilage should be captured by objective measurement in vivo and in real time. Energy spectrum CT (GE's Revolution CT 256-Slice Scanner) is an instrumental tool which offers temporal and spatial resolution superior to typical CT and can non-invasively obtain dynamic sequence images of subjects in different laryngeal functional states.[1–3]

The Euler angles are three angles to describe the orientation of a rigid body with respect to a fixed coordinate system. The movement of the arytenoid cartilage relative to the cricoid cartilage is similar to the aircraft to the earth. The arytenoid cartilage (aircraft), in addition to rotation, also has displacement relative to the cricoid cartilage (Earth—a stationary reference). Based on this, we will apply the Euler angles (matrix conversion between different coordinate systems) to the description of the motion of the arytenoid cartilage and the cricoid cartilage.

METHODS

Subjects

Five subjects received a neck CT examination for disease unrelated to voice in Zhongshan Hospital, Xiamen University

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from October 2017 to July 2018. Two males and three females were recruited, with an average age of 51 years. The conditions for inclusion included normal voice as determined by acoustic analysis, asymptomatic, normal physical examination, and no vocal training or history of voice complaints. Participants signed ethical informed consent forms. Smooth bilateral vocal fold edges, symmetrical vocal fold movement, and absence of laryngeal lesions were confirmed via stroboscopic laryngoscopy examination. Two patients were excluded due to inability to follow instructions and insufficient cartilage calcification for imaging.

Dynamic CT Scan and Reconstruction

An otolaryngologist trained participants in the study procedure prior to scan—a 2.5-second inspiration followed by production of /i/ at a comfortable pitch for about 3 seconds until the end of the scanning cycle. The scanning range was about 8 cm, including the epiglottis cartilage to the first tracheal ring, and the radiation dose was less than 2 mSv. The reconstruction thickness was 0.625 mm after scanning and 10 reconstructed frames were obtained. A total of 1280 original DICOM files can be obtained and the original data were imported into Mimics Medical 19.0, and the 10 consecutive frames from inspiration to pronunciation can be obtained (Fig. 1).

Spatial Calibration of Cricoid and Arytenoid Cartilages

Calibration of cricoid and arytenoid cartilages. The reconstructed cartilage model was imported into commercial imaging software (Mimics 3-matic Medical version 19.0, Leuven, Belgium). Analysis coordinate points in the original coordinate system were established and four coordinate points were calibrated. Taking the reconstructed image of the first frame as an example, three points which outline the shape of the arytenoid cartilage (point O, point 1, and point 2) were calibrated. Point 1 was taken at the vocal process, point 2 was taken at the muscular process, and point O was marked in Figure 2. Another point (point C) was calibrated on the highest medial point of the articular surface of the cricoid cartilage (Fig. 2). Based on the principle of mirror symmetry, four points corresponding to the opposite arytenoid cartilage were also identified.

Determining coordinates from the calibration point in the original coordinate system and transforming

OBTAINING THE COORDINATE VALUE OF THE CALIBRATION POINT. After each calibration point was positioned, the coordinate value of the original coordinate system X, Y, Z axis was automatically determined by the software. Figure 3 shows an example of this calibration.

TRANSFORMATION OF COORDINATE VALUES OF CALIBRATION POINT. In combination with the previous research[4–6] on the motion mode of the arytenoid cartilage,

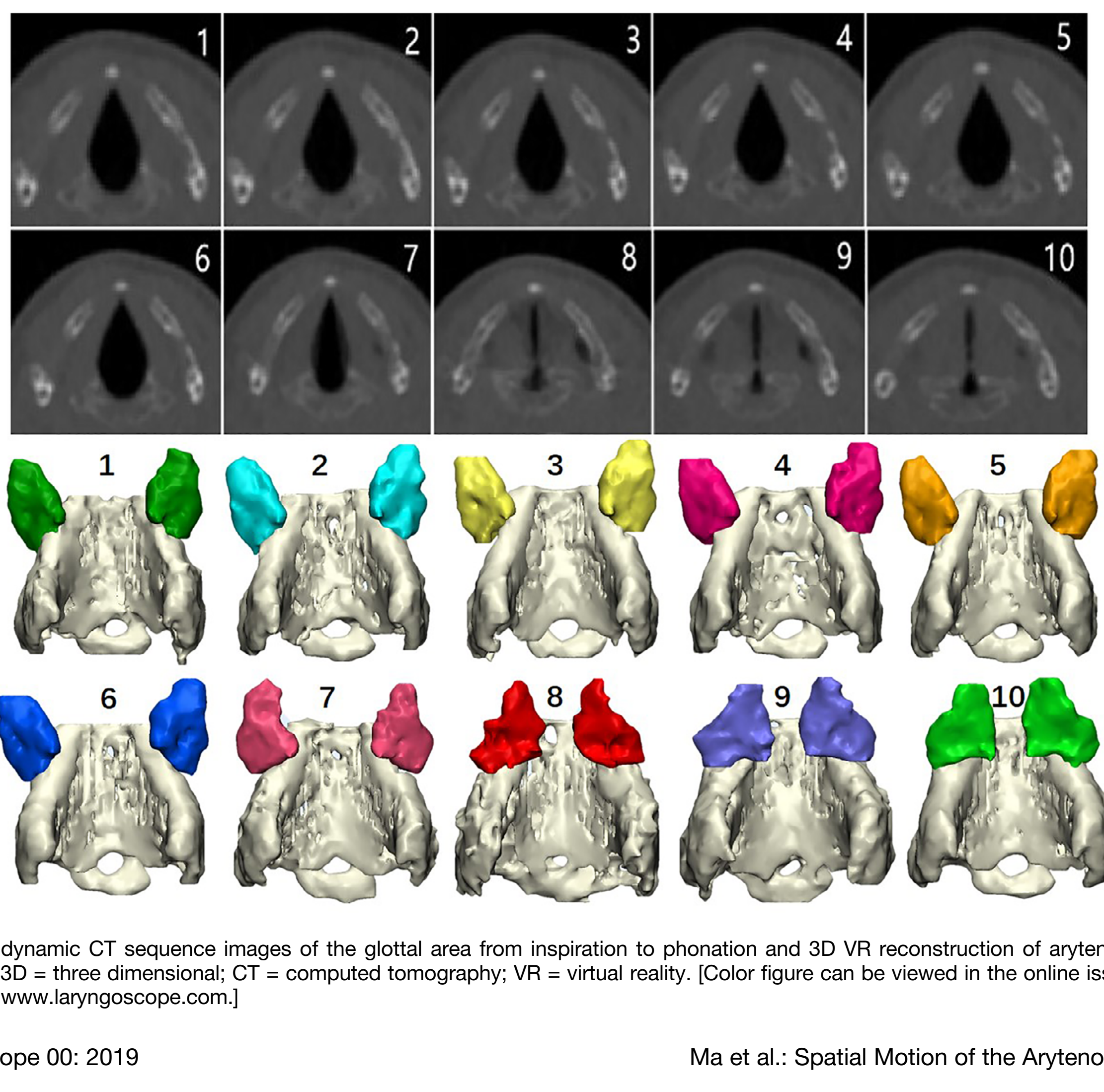

Fig. 1. The dynamic CT sequence images of the glottal area from inspiration to phonation and 3D VR reconstruction of arytenoid cartilage movement. 3D = three dimensional; CT = computed tomography; VR = virtual reality. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

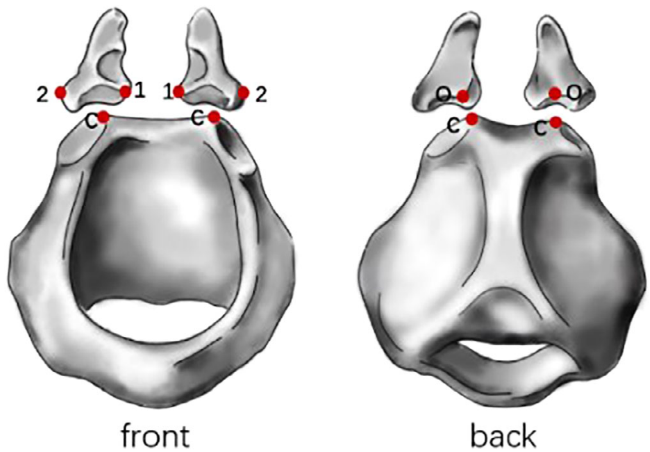

Fig. 2. Diagram of the coordinate points of the arytenoid cartilage and the cricoid cartilage (red point) [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

two transformations of the original coordinate values of the software were made. First, according to the right-hand principle of physics, the original coordinate system was spatially transformed to obtain the transformed coordinate system (X′ = X; Y′ = Z; Z′ = −Y). For simplicity, the apostrophe was omitted to represent the transformed coordinate system (Fig. 3). Second, the cricoid cartilage was assumed to be immobilized and the coordinate values of the cartilage point 1, point 2 and point O were converted based on the motion changes of the point C coordinate value of the cricoid cartilage.

Establishing a stationary coordinate system and a moving coordinate system. Calibration point C on both sides of the cricoid cartilage was used as the origin of the stationary coordinate system and the left and right stationary coordinate systems were established, respectively. The three coordinate points calibrated on the arytenoid cartilage were used to establish a motion coordinate system. In combination with previous studies.[4–6] the motion of the arytenoid cartilage was least in the posteromedial region, and the prominent point O of the posteromedial region of arytenoid cartilage was taken as the origin of the motion coordinate system as shown in Figure 4.

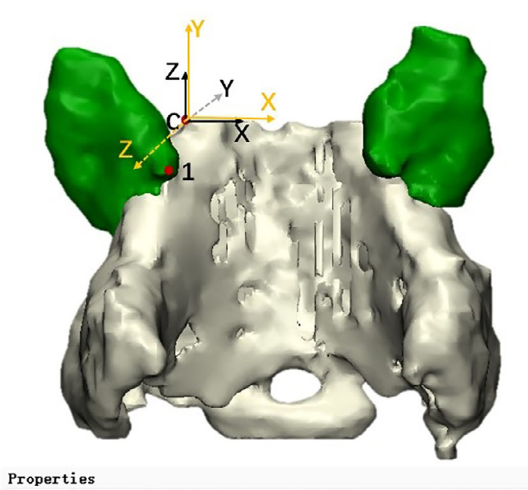

Fig. 3. The coordinate values of the calibration points in the original coordinate system were obtained and converted (frontal view) [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

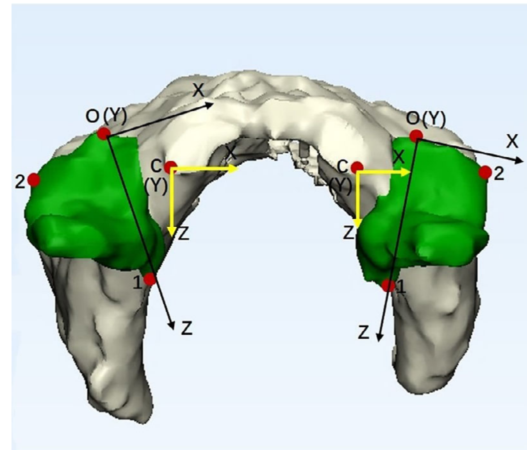

Fig. 4. Diagram of the coordinate points of the arytenoid cartilage and the cricoid cartilage (red point), the stationary coordinate system (yellow) and the motion coordinate system (black). The plane where the three points (1, 2, and O) were located was the Oxz plane, and the line formed by point O and point 1 was the *z*-axis. The coordinate is defined in the right hand principle (transverse view) [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

Calculating the displacement and rotation angle of the arytenoid cartilage relative to the cricoid cartilage

The motion of the arytenoid cartilage relative to the cricoid cartilage can be deconstructed into two terms: translation and rotation. The origin of the stationary coordinate system (point C) was taken as the reference, and the displacement between the origin of the motion coordinate system (point O) and point C represents the translation displacement between them. The translational displacement can be decomposed into displacements in the *x*-axis (in the medial-lateral direction), the *y*-axis (in the superior-inferior direction), and the *z*-axis (in the anterior-posterior direction). Positive and negative values represent the direction of displacement (see Appendix for details).

Two different frames of reference were used to describe the spatial rotation of arytenoid cartilage. The first used the orientation of the stationary coordinate system of the cricoid cartilage as the starting point and calculated the Euler angle of rotation of the moving coordinate system of the arytenoid cartilage, equivalent to describing the spatial position of arytenoid cartilage relative to the stationary coordinate system. The second calculated the Euler angle of the motion coordinate system of the arytenoid cartilage from the first frame to the next frame, equivalent to describing the relative rotation of the arytenoid cartilage between the two frames. The positive and negative values of the two rotation angles were determined according to the right-handed spiral rule. The first and second angles of rotation were combined to describe the true motion trajectory of arytenoid cartilage during inspiration and phonation. The cartilage rotation was limited by the articular capsule and the actual angle of rotation was minor. To calculate the angle and describe the spatial orientation, a second type of Euler angle (see Appendix for details) was used. The initial coordinate system was set as Oxyz, and the new coordinate system obtained after rotation was Ox′y′z′. Given any rotation the coordinates can be superimposed as Ry(α)Rx(β)Rz(γ) rotating around the coordinate axis, so that the rotation transformation matrix Ω(α,β,γ) = Ry(α)Rx(β)Rz(γ).[7] For any point R, the coordinate transformation relationship between the two coordinate systems satisfied

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \Omega(\alpha, \beta, \gamma) \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Three values of Euler angles αβγ can be calculated using the coordinate values before and after rotation (see Appendix for details). α indicates the angle of medialization and lateralization of the arytenoid cartilage around the *y*-axis, that is, the long axis of the human body. β represented the angle of forward backward tilt of the arytenoid cartilage around the *x*-axis, that is, the angle of horizontal inclination and retroversion. γ Represented the angle at which the arytenoid cartilage rolled around the *z*-axis medially and laterally. The positive and negative values of αβγ represented the difference in rotation. The positive and negative values of the rotation angles were determined according to the right-handed spiral rule (see Appendix for details). The right thumb pointed to the axis and the direction of the bent four fingers defined counter-clockwise rotation as positive and clockwise rotation as negative.

RESULTS

We found that the cricoid cartilage displaced inferiorly during inspiration, and the glottal area increased gradually. During phonation, the cricoid cartilage turned to displace superiorly, the glottal area decreased gradually, and the glottal area was the smallest when the glottis closed. Combining the displacement of the cricoid cartilage and the glottal area, we took the displacement of the cricoid cartilage from inferior to superior as the turning point of inspiration and phonation. At this moment the glottal area was greatest, which was the point of maximum inspiration.

TABLE I.
Glottal Area and Displacement of Cricoid Cartilage.

Subject	Frame	Displacement of cricoid cartilage (mm)			Glottal area (mm²)
		X	Y	Z	
1	1	/	/	/	118.6
	2	0.0	−1.5	0.1	118.1
	3	0.0	−1.2	−0.9	120.8
	4	0.0	−0.9	0.0	122.7
	5	0.0	−2.3	−1.6	129.1
	6	0.0	0.8	0.8	128.4
	7	0.0	1.4	−0.4	106.0
	8	0.0	5.1	1.4	33.0
	9	0.0	3.4	0.8	37.2
	10	0.0	0.7	0.2	36.8
2	1	/	/	/	81.6
	2	0.0	−1.6	−0.3	87.1
	3	0.0	−0.1	−0.2	88.5
	4	0.0	−0.6	−0.1	88.5
	5	0.0	−1.4	0.1	89.1
	6	0.0	0.4	−0.2	68.7
	7	0.0	0.5	0.6	54.0
	8	−0.1	8.0	−0.9	21.5
	9	0.0	2.4	−0.5	40.3
	10	0.0	1.9	−0.5	44.5
3	1	/	/	/	191.4
	2	0.0	0.0	0.0	189.4
	3	0.0	0.1	0.2	164.9
	4	0.0	0.6	0.0	18.6
	5	0.0	0.8	0.2	6.9
	6	0.0	0.6	0.2	9.8
	7	0.0	0.3	0.1	15.4
	8	0.0	1.5	0.5	40.7
	9	−0.1	2.7	0.9	34.7
	10	−0.1	1.4	0.3	32.7

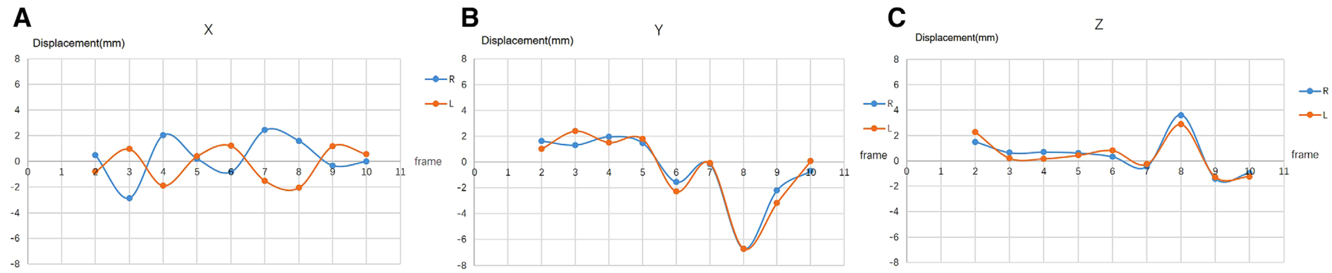

Fig. 5. Displacement curve of the arytenoid cartilage posterior site relative to the cricoid cartilage on the *xyz* axis. Each lattice on the horizontal axis represents 0.56 s and each lattice on the vertical axis represented 2 mm. A) displacement on the *x*-axis; B) displacement on the *y*-axis; C) displacement on the *z*-axis. Blue = left arytenoid; red = right arytenoid. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

A. Determination of inspiration and phonation: Combining changes in glottal area and movement of the arytenoid and cricoid cartilages (Table I), in terms of subject 1, we determined the first to fifth frames as the inspiration process, the fifth frame was the maximum inspiratory phase, and the sixth to 10th frames were phonation.
B. Displacement curve of the arytenoid cartilage relative to the cricoid cartilage on the XYZ axis (Fig. 5; see Appendix for details).
C. Two types of rotation description of the arytenoid cartilage (Fig. 6; see Appendix for details).

The data of displacement and rotation angle of the arytenoid cartilage seen as in Table II.

Based on the displacement of the cricoid cartilage and the displacement and rotation angle of the arytenoid cartilage during inspiration and phonation in three subjects, the following conclusions were drawn:

1. The motion of the cricoid cartilage: The cricoid cartilage primarily demonstrated superior and inferior displacement. The displacement primarily occurred inferiorly during inspiration, possibly related to the speed of inspiration. During phonation, the displacement of the cricoid cartilage was mainly superior. When the glottis closed, the superior displacement was about 5–8 mm within 0.56 s. There was almost no medial-lateral displacement and little anterior-posterior displacement (about 1 mm).
2. The displacement and rotation angle of arytenoid cartilage: The motion of bilateral arytenoid cartilage was basically symmetrical, but not completely synchronous. A. During inspiration, the arytenoid cartilage was displaced superiorly approximately 1–2 mm each 0.56 s. There was little change to anterior-posterior displacement and an alternating medial-lateral movement. The rotation angle was subtle, with slight rotation around the *xyz*-axis, and the range of variation was about 5–10 degrees. B. During phonation,

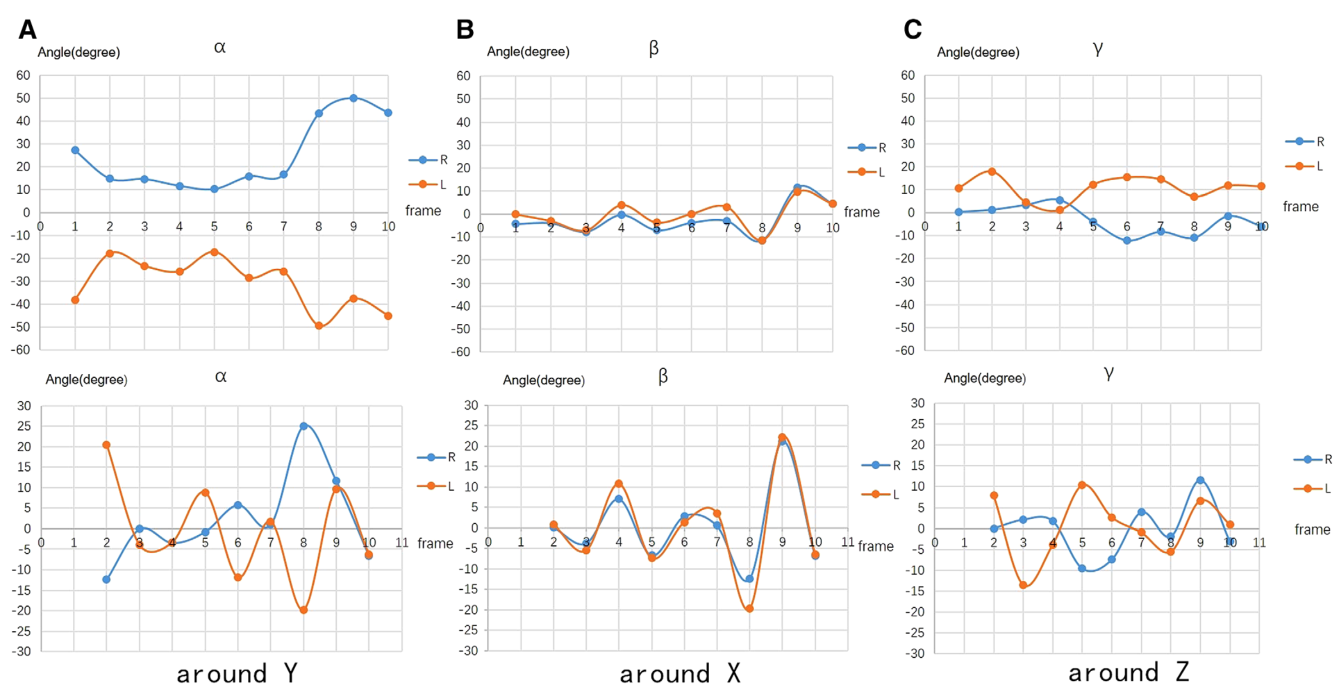

Fig. 6. Angle change curve of arytenoid cartilage relative to cricoid cartilage rotating around *yxz*-axis in turn (above). The relative rotation angle of arytenoid cartilage around the *yxz*-axis in sequence in two adjacent frames (below). A) change in angle α of medialization and lateralization of arytenoid cartilage around the *y*-axis, (ie, the long axis of the human body); B) change in angle β of arytenoid cartilage around the *x*-axis (ie, forward and backward tilt in the horizontal direction). C) change of angle γ of arytenoid cartilage rolling around the *z*-axis. Blue = right arytenoid; red = left arytenoid [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

TABLE II.
Displacement and Rotation Angle of Arytenoid Cartilage.

		Displacement of arytenoid cartilage (mm)						The second rotation angle of arytenoid cartilage (degree)					
		Left			Right			Left			Right		
Subject	Frame	X	Y	Z	X	Y	Z	α	β	γ	α	β	γ
1	**1**	/	/	/	/	/	/	/	/	/	/	/	/
	2	−0.8	1.0	2.3	0.5	1.6	1.5	20.5	0.9	7.8	−12.4	0.2	0.0
	3	1.0	2.4	0.2	−2.9	1.3	0.6	−4.0	−5.5	−13.5	−0.1	−3.7	2.1
	4	−1.9	1.5	0.2	2.1	2.0	0.7	−3.3	10.8	−3.8	−3.4	7.1	1.7
	5	0.4	1.8	0.4	0.2	1.5	0.6	8.8	−7.4	10.4	−0.8	−6.7	−9.6
	6	1.2	−2.3	0.8	−0.8	−1.6	0.3	−11.9	1.3	2.7	5.8	2.8	−7.5
	7	−1.5	−0.1	−0.3	2.4	−0.2	−0.5	1.7	3.6	−1.0	1.0	0.6	3.9
	8	−2.1	−6.7	2.9	1.6	−6.7	3.6	−19.8	−19.7	−5.5	25.0	−12.4	−1.9
	9	1.2	−3.2	−1.3	−0.3	−2.2	−1.4	9.7	22.2	6.7	11.7	21.2	11.6
	10	0.6	0.1	−1.2	0.0	−0.7	−0.9	−6.2	−6.4	0.9	−6.6	−6.8	−3.1
2	**1**	/	/	/	/	/	/	/	/	/	/	/	/
	2	−1.6	1.7	0.0	0.7	0.9	−0.2	−0.9	−5.5	−49.6	−8.3	−1.3	60.2
	3	1.0	−1.8	1.4	−0.6	−1.0	−0.1	10.1	−10.6	45.1	−4.8	−3.8	−55.5
	4	−0.2	1.2	−1.6	−1.7	0.3	−0.6	−1.7	−1.9	2.9	−1.3	−4.0	−1.4
	5	−1.8	1.0	0.8	2.0	1.3	0.9	0.6	7.4	8.0	7.5	3.5	−2.3
	6	0.8	0.5	2.0	−0.6	0.8	0.0	−6.1	−5.3	−2.7	4.2	−0.3	3.7
	7	3.8	−2.0	0.4	−2.3	−4.4	2.1	−11.0	−12.7	−8.6	4.2	−21.3	−15.4
	8	−1.6	−6.4	2.0	3.7	−4.0	1.2	−17.3	−22.7	−3.5	11.7	−16.1	22.3
	9	0.3	−1.2	1.1	−1.8	−1.4	−0.4	−10.3	7.9	12.4	8.0	8.2	−9.3
	10	−1.3	−1.1	−0.4	−0.3	−0.3	2.9	10.9	−2.0	−11.6	9.7	−4.5	2.1
3	**1**	/	/	/	/	/	/	/	/	/	/	/	/
	2	−0.0	0.3	−0.3	0.0	0.3	0.5	3.4	2.2	8.0	1.4	−1.9	−5.1
	3	0.2	−0.1	−0.2	−0.0	0.3	0.3	−3.4	0.2	−7.1	6.8	3.4	14.3
	4	−0.2	0.6	3.4	0.0	0.9	2.7	−41.5	21.4	−21.4	31.0	15.2	33.4
	5	−0.8	−4.4	0.2	0.9	−3.9	0.5	1.9	−3.5	10.6	−5.0	3.5	−10.8
	6	0.8	0.1	0.4	−0.9	0.4	0.5	−7.0	−2.0	−3.7	−2.4	−0.2	9.9
	7	−0.6	0.2	−0.3	0.9	−0.4	−0.1	3.0	0.2	−13.4	1.3	1.2	3.3
	8	0.6	−0.9	0.2	−0.8	−0.9	0.1	7.5	−8.2	3.7	−0.7	−5.9	−12.1
	9	−0.0	0.8	−1.2	−0.0	1.1	−1.2	−2.1	−5.6	16.7	2.0	−6.0	−4.7
	10	0.0	−0.7	−0.1	0.0	−2.3	0.1	0.3	−1.1	14.1	3.9	1.16	−13.3

the displacement and rotation angle of the arytenoid cartilage changed most at the moment of the closed phase of the vocal fold vibratory cycle. The displacement of the arytenoid cartilage was mainly inferior, anterior and medial, with an inferior displacement of about 4–6 mm, an anterior displacement of about 2–4 mm and a medial displacement of about 1–2 mm. The motion of the arytenoid cartilage mainly consists of medial rolling, and there is an alternating movement of anterior-posterior tilting. The arytenoid cartilage rolled medially (about 20–40 degrees within 0.56 s) accompanied by anterior-posterior tilting (about 15–20 degrees within 0.56 s).

DISCUSSION

In this study, dynamic CT combined with Euler transformation in physics was used to reproduce the real spatial motion trajectory and quantitatively describe the spatial motion characteristics of the arytenoid cartilage. It is expected that by comparing the subtle differences of spatial motion characteristics of the arytenoid cartilage, the etiology and classification of vocal fold dyskinesia diseases can be determined to aid in differential diagnosis of unilateral vocal fold paralysis, unilateral cricoarytenoid dislocation, or anterior or posterior cricoarytenoid dislocation.

The research on the motion of the arytenoid cartilage has mainly focused on the scanning and reconstruction of the excised larynx and static CT. Furthermore, previous studies that used static CT only captured a single plane of movement at a given point in time, which could not represent the movement of the arytenoid cartilage in the functional state of the larynx. For example, Ardran et al.[4] found that the arytenoid cartilage inclined about 45 degrees to the outside of the arytenoid articular surface when the glottis opened, which was similar to the angle change described by the first rotation of the arytenoid cartilage found in our study. The right medialization was 43.42 degrees and the left medialization was 49.41

degrees. When the glottis closed, the arytenoid cartilage moved inferiorly and anteriorly, and rolled medially at an arc of about 40 degrees. Storck et al. found that when the arytenoid cartilage moved from the "respiratory" position to the "phonation" position, it rotated inward, swayed inward, and slid forward.[5] We also observed that, at the moment of glottal closure, the motion of the arytenoid cartilage mainly consisted of medial rolling, and there was an alternating movement of anterior-posterior tilting. The arytenoid cartilage rolled medially (about 20–40 degrees within 0.56 s) and was accompanied by anterior-posterior tilting (about 15–20 degrees within 0.56 s). Liu et al. found that the cricoarytenoid joint capsule was loose and folded, and the dimension of the cavity was much larger than that of the articular surface of the cricoarytenoid joint.[6] The contact area between the cricoid cartilage and the arytenoid cartilage was very small, especially in the superior and medical aspects which distanced the arytenoid cartilage from the cricoid cartilage. The posterior part of the cricoarytenoid joint capsule was significantly strengthened by rich elastin fibers. Our results showed that during phonation the displacement of the arytenoid cartilage was mainly inferior, anterior, and medial; the displacement of superior-inferior was larger than other direction; and there was almost no posterior displacement. Therefore, we speculated that the displacement of arytenoid cartilage may be related to the loose local distribution of the arytenoid capsule. Liu et al. also found that there may be a jumping of the arytenoid cartilage on the cricoid cartilage, and the extent may not be even.[6] Considerable jumping may occur at the superior, anterior and medial aspects of the joint. The jumping coordinated with other movements of the arytenoid cartilage, such as sliding, rocking, and rotation. The direction of jumping coincides exactly with the direction of displacement of arytenoid cartilage in our study, and there may be some correlation between them. Neuman et al. found that the arytenoid cartilage mainly has an internal rotation around the y axis, and the medialization angle was $13^\circ \pm 1^\circ$.[8] The rotation around the x-axis was small, most of them were forward tilting, and the lateralization around the z-axis was small. We also observed that the arytenoid cartilage rotated largely medially around the y-axis during the closed phase of the vocal fold vibratory cycle, and medialized about 20–25 degrees within 0.56 s, which was different from the angle change observed by Neuman et al. The tilting around the x-axis was a dynamic alternating process. At the moment of glottal closure, the anterior-posterior tilting was about 15–20 degrees within 0.56 s. The reason for this difference may be the fixed position for measurement used in static CT, whereas we were concerned with dynamic measurement. Wang et al. manipulated the arytenoid cartilage in an omnidirectional motion from medialization to lateralization, imaging from the coronal, sagittal, and transverse directions, generating a 3D map of the arytenoid joint motion by recording and editing the static frame.[9] The displacement of the vocal process and the muscular process revealed that the vocal folds were mainly moved laterally during abduction, with little superior movement, and little or no anterior and posterior movement. We observed that the displacement of arytenoid cartilage was mainly superior during inspiration, and the displacement of the arytenoid cartilage was about 1–2 mm within 0.56 s. The change of displacement from anterior to posterior was not significant. The difference may be related to the displacement of the posteromedial point O of the arytenoid cartilage, rather than the displacement of the vocal process. Probst et al. found that when the arytenoids rotate by sliding from anterior to posterior on the cricoid facets about a primary axis of motion aligned from medial, posterior, and superior to lateral, anterior, and inferior, vocal processes shift positions along a plane obliquely oriented from anterior and medial to posterior and lateral, and from inferior and medial to superior and lateral.[10] We found that the arytenoid cartilage also moved anteriorly-posteriorly, superiorly, and laterally during inspiration and phonation. Sellars et al. found that the cricoid cartilage was often asymmetrical between the left side and the right side.[11] Therefore, the location of the vocal folds of the two arytenoid cartilages may be asymmetric. Although this asymmetry, the final movement of each arytenoid cartilage ensures that the glottis is opened and closed accurately at the same time, which coincides with our finding that the movement of the bilateral arytenoid cartilage is basically symmetrical, but not completely synchronous.

This study provides a viable method for recording and measuring the real-time motion of arytenoid cartilage. The primary challenge encountered in the study was the calcification of cartilage. Poorly calcified cartilage cannot be reconstructed to obtain a general shape, and thus cannot be accurately calibrated and analyzed, resulting in error in the research results. We will further try to study the motion of cartilage by calibrating soft tissue instead of cartilage. In the future, the movement characteristics of the arytenoid cartilage under a larger sample size and various diseases will be the direction of further research. Another research challenge to address is the difficulty of calibrating the posterior position of the arytenoid cartilage. We calibrated the apex, vocal process, muscular process, and posterior position of the arytenoid cartilage simultaneously in the easily calibrated image of the posterior position and measured the spatial position between the four points. In images for which we could not calibrate the posterior position, we calculated the posterior position by calibrating the apex, vocal process and muscular process of the arytenoid cartilage.

CONCLUSION

Dynamic CT recordings of arytenoid cartilage movement can be combined with Euler transformations as a tool to study the spatial characteristics of laryngeal structures during phonation.

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