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Three-Dimensional Reconstruction of Human Vocal Folds and Standard Laryngeal Cartilages Using Computed Tomography Scan Data

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Summary

Three-dimensional (3D) computer models of the human larynx are useful tools for research and for eventual clinical applications. Recently, computed tomography (CT) scanning and magnetic resonance imaging (MRI) have been used to recreate realistic models of human larynx. In the present study, CT images were used to create computer models of vocal folds, vocal tract, and laryngeal cartilages, and the procedure to create solid models are explained in details. Vocal fold and vocal tract 3D models of healthy and postsurgery larynges during phonation and respiration were created and morphometric parameters were quantified. The laryngeal framework of eight patients was also reconstructed from CT scan images. For each cartilage, morphometric landmarks were measured on the basis of their importance for biomechanical modeling. A quantitative comparison was made between measured values from the reconstructions and those from human excised larynges in literature. The good agreement between these measurements supports the accuracy of CT scan-based 3D models. Generic standard models of the laryngeal framework were created using known features in modeling softwares. They were created based on the morphometric landmark dimensions previously defined, preserving all biomechanically important dimensions. These models are accessible, subject independent, easy to use for computational simulations, and make the comparisons between different studies possible.

Keywords

Human larynx; Three-dimensional reconstruction; Computed tomography; Morphometric measurement; Laryngeal framework

Introduction

Realistic biomechanical laryngeal models may find significant clinical applications to model the effects of treatment on laryngeal disorders. High fidelity models are beneficial for examining several different phonation aspects such as aerodynamics, acoustics, vocal fold vibrations, kinematics of cartilage motion, and mechanical properties of vocal fold tissue. In the medical field, they can be used for surgical planning and analysis of laryngeal anomalies.¹ Of particular importance is the morphology of the laryngeal framework, which, along with the action of muscles and their locations, determines cartilage motion and

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consequently the vocal folds postures. As a result, accurate anatomical data of the laryngeal cartilages and vocal fold geometry are needed to create a realistic three-dimensional (3D) laryngeal model.

Computed tomography (CT) scan images have been used to create realistic 3D vocal fold and vocal tract geometries for the purpose of studying laryngeal anomalies. For instance, the asymmetry of vocal folds in patients with immobility² and unilateral vocal fold paralysis before and after treatment³ have been studied. Two- or simplified three-dimensional vocal folds and vocal tract geometries have been mostly used for computational fluid dynamics (CFD), finite element (FE), and fluid structure interaction simulations. Less attention has been paid to the creation of realistic vocal fold and vocal tract models for computer simulations. Gökcan et al⁴ used accurate larynx geometries for computational analysis. Šidlof et al⁵ used plaster casts to capture the vocal fold profiles from excised human larynxes. In this approach, the geometry of the excised larynx is not very realistic because the thyroarytenoid muscle is not active.⁵

Several morphometric measurement data of the laryngeal framework from cadaver larynxes can be found in literature.^{1,6–9} The CT scans and MRI have been used to create 3D computer models of laryngeal cartilages.^{10–12} However, the dimensions of the complex cartilage geometries alone are insufficient to recreate the laryngeal cartilage framework. Models so far based on actual laryngeal framework data are not repeatable unless one has access to the specific CT or MRI data used, and follow the same segmentation steps as in the original study.

One objective of the present study was to create 3D solid models of vocal folds, vocal tracts, and laryngeal cartilages to be used for computational simulations. Manual and automatic image segmentations were performed on depersonalized CT scan data to create 3D models of the larynx. Human-specific 3D models of the vocal folds and the vocal tract of subjects were obtained during phonation and breathing, and geometrical differences were investigated. Geometries of thyroid, cricoid, and arytenoid cartilages were reconstructed; and to evaluate the precision of the segmentation procedure, biomechanically important dimensions of the generated cartilages were compared with cadaver measurements data published in the literature. Mesh smoothing and surface treatment methods were used to remove any artifacts and sharp edges that could affect the convergence of computer simulations.

The main objective of the present study was to create “cartilage standard models.” Preserving all biomechanically important dimensions, CT scan-based cartilage geometries were recreated using known geometrical features in modeling softwares. These “cartilage standard models” are accessible, subject independent, and can be considered as generic laryngeal cartilage geometries for use in computer simulations.

Methodology

CT scan data

In the present study, data from 12 anonymous subjects were provided from the Montreal General Hospital; however, only eight were used. Three data sets were discarded on the basis of very poor gray-level intensity contrast between cartilage and surrounding soft tissue and poor resolution. Another set was deemed inadequate owing to movement of the patient during the scanning process. All data are related to male subjects. One set of the CT data is related to postsurgery images for a patient with cancer. The CT scanning was performed using a General Electric Discovery machine with tube potential of 120 kV. There are differences between the CT imaging settings from one case to another. For instance, the tube

current and slice thickness ranged from 100 to 131 mA and 0.6 to 1 mm, respectively. However, the criteria for including and excluding one set of data are the gray-level intensity contrast between the region of interest and its surroundings.

Segmentation

Segmentation was done using an open-source software, *ITK-Snap*,¹³ which allows the simultaneous triaxial display of the sagittal, coronal, and transverse medical images, as well as a 3D view of the segmented structure. A semiautomatic segmentation procedure was used based on ITK-Snap's region-based sectioning method.¹³ The gray-level intensity interval for each geometry was determined by displacing the crosshairs on the input image in the region of interest. The upper and lower thresholds values were fed into the “preprocess image” window, with the smoothness parameter set to its maximum.

To save time and minimize user error, the segmentation process was first done using ITK-Snap's automatic segmentation feature. The intensity contrast between air and tissue is high in CT images. Therefore, vocal folds and the vocal tract boundaries were clearly identified and no further manual editing was required. However, manual segmentation tools were used in some cases to edit the cartilage structures after automatic segmentation. For instance, certain elements of the arytenoid and cricoid cartilages could not be well visualized in CT scan images, especially those composed of elastic cartilage such as the arytenoid apices.¹⁴

Morphometric measurements

The STL files created from ITK-Snap were converted into solid bodies in *Solidworks* (2011) using the Surface Wizard from the Scan to 3D add-in. Dimensions were computed according to the morphometric measurements defined by Tayama et al¹ for the purpose of biomechanical modeling.

Surface treatment or mesh smoothing

Surface treatment was necessary to eliminate the sharp edges and artifacts in the reconstructed geometries, as they can affect the convergence of CFD or finite-element simulations. An open-source software for processing and editing of unstructured 3D triangular meshes, *Meshlab* was used. Among several different mesh smoothing methods available in the software, better results were obtained by using the Laplacian method.¹⁵ Reconstructed geometries were subjected to different numbers of smoothing iterations, which increased with the size of the geometry.

Results

Laryngeal cartilages

The 3D reconstructed models and morphometric measurement—The 3D reconstructed cartilages from one set of CT scan images are shown individually and assembled in Figure 1. All measurement definitions and landmarks are schematically shown on the reconstructed geometries in Figure 2A-C. The results of the morphometric measurements performed on the segmented thyroid, cricoid, and arytenoid cartilages are recorded in Tables 1–3, respectively. The total number of cartilages for which measurements were obtained is shown in each table. The number of models associated with each measurement varied between cartilages and landmark points. One thyroid was excluded owing to physiological anomalies. Two arytenoids could not be accurately segmented owing to low visibility in the CT scan images. Moreover, the joint facets proved to be the most difficult features to observe. This may be owing to the differences in joint physiology and its soft tissue percentage, which is difficult to see using CT.¹⁶ For each morphometric

landmark, the mean and standard deviation were calculated. The accuracy of the segmentation procedure was verified by calculating the relative difference between the results from Tayama et al¹ and the results from the present study. An average relative difference is shown in the last row of each table.

Laryngeal cartilage standard models: Although much research has been done on the morphology of the thyroid, cricoid, and arytenoid cartilages, an understanding of the relationships between the cartilages is of primary importance for creating a model for the purpose of biomechanical analysis. To obtain functional models, the 3D reconstructed models from CT images were analyzed and simplified, while preserving the biomechanically important dimensions. Laryngeal cartilage standard models were created and based primarily on the morphometric dimensions recorded in Tables 1–3. Additional needed dimensions were obtained from measurements performed on the geometries reconstructed from CT images.

The models were constructed using splines, points, and simple geometrical shapes. Splines were used to outline sketches by joining different selected points. They also served as guide curves to delimit the curvature of the cartilage. The points marked important locations measured from the reconstructed geometries. Details about the creation of the standard models and engineering drawings showing the important cross-sections and dimensions for the cartilages are presented in the Appendix section. The reconstructed computer models are available in the Supplementary material of the article.

Vocal tract and vocal fold models

The CT scan images for different postures of the larynx and vocal folds were used, two of which are shown in Figure 3. The cross-section of the 3D vocal tract model of the first set of images, before and after smoothing, is illustrated in Figure 3A and B. A large gap between the vocal folds can be observed in these images showing that this set was obtained during respiration. No abnormality was visible in the images and according to an otolaryngologist (third author) and our radiologist collaborator, the subject can be considered geometrically healthy. Sharp edges were removed after smoothing, making the geometry ready for further numerical simulations. Vocal folds, false folds, ventricles, subglottal, and supraglottal regions are shown in Figure 3B.

The second set of CT data was related to the postsurgery images of a patient with cancer and was obtained during phonation with the vocal folds partially closed. The smoothed cross-section from the 3D solid model of the postsurgery larynx is shown in Figure 3C. Asymmetry between left and right vocal folds can be observed because cancerous tissue was removed from the left vocal fold.

In a human larynx, the vocal tract and glottis are defined as the hollow space within the larynx and between the vocal folds, respectively. In numerical flow simulations, these cavities substitute the computational domain. The 3D vocal tract model and the corresponding 2D midsagittal images for both healthy and postsurgery larynges are shown in Figures 4 and 5, respectively.

Three-dimensional models of the vocal tract were built with various sizes depending on the desired application and the visible sections in CT scan images. For instance, geometries that only consist of vocal folds can be used for structural and vibration analysis. However, more accurate results may be obtained for acoustic and CFD simulations if the geometries include the upper and lower airways. In Figure 6, a large portion of the trachea, the vocal folds, the pharynx, the oral cavity, and the beginning of the nasal cavity are visible, permitting a more

realistic 3D model to be used for fluid flow simulation in the vocal tract and the upper airway.

Discussion

Comparisons between morphometric measurements obtained from 3D solid models and cadaver data

For the purpose of reconstructing the laryngeal framework and vocal folds, CT scan was used in this study because it is well suited for the visualization of ossified structures. *In vivo* visualization of the human larynx is believed to be more accurate than measurements on excised larynges because the geometry of the larynx after excision may be altered. Therefore, models created from patient scans are preferred as they conserve the realism of the muscles and the larynx. The morphometric features defined by previous studies^{1,6} were easily measured on the reconstructed geometries and accurate within a relatively small range of error.

During the segmentation process, the thyroid was found to be the easiest cartilage to section owing to its large size and high ossification levels. Generally, manual editing was limited to the interior of the lamina thickness, which is the last part of the cartilage to calcify.¹⁶ It is noteworthy to mention that manual editing of this part did not alter the measurements, but could potentially determine whether the imported body in *Solidworks* was a solid body or a surface body. The dimensions of the segmented 3D models were comparable with those of Tayama et al,¹ both in terms of average relative difference (7.14%) and standard deviations. These data are shown in Table 1. The largest relative difference (16.41%) occurred for the angle between the thyroid laminae (). This was expected because the standard deviation calculated by Tayama et al¹ was also very large (10.15).

Some aspects of the cricoid cartilage were difficult to segment. For instance, the inferior section of the cricoid cartilage displayed significant inhomogeneity in its laminae. Automatic segmentation was thus performed twice using different gray-level intensity intervals to minimize the required amount of editing. A significant difference of 21.05% was recorded for the average height of the cricoid measurement (F–F) in Table 2. The standard deviations were twice those for the data by Tayama et al,¹ 3.40% and 1.68%, respectively. This may be because the rear boundaries are blurry near the inferior part of the cricoid, making the gray-level intensity interval very similar to that of the surrounding soft tissue. It was therefore necessary to superimpose previously well-segmented images onto the current image and define the remainder of the structure manually, which increased the error. Nevertheless, the average relative difference between the computed values and those of Tayama et al¹ was only 6.24%, suggesting accurate segmentation of the cartilage.

The pair of arytenoid cartilages were the hardest to segment and required the greatest amount of manual editing out of the three cartilages. The arytenoid cartilages gray-level intensity interval overlapped with that of the cricoid, which may have caused the software to indiscriminately assign the same label to both structures. The arytenoids are mainly composed of two cartilages. The body is composed of hyaline cartilage, which ossifies over time, and the apices are composed of elastic cartilage, which never ossifies.¹⁴ The vocal and muscular processes are thus more difficult to detect using CT imaging. The low visibility of the arytenoid apices may account for the relatively large differences in Table 3 for the distance measured between the vocal and muscular processes (16.96%— measurement R–S), and the distance between the vocal process and center of the cricoarytenoid facet (29.47%—measurement R–X).

Cartilage standard models

The geometry of laryngeal cartilages is quite complex, and shows large differences in size and shape between subjects. For these reasons, it is very difficult to develop standard-sized medical tools.¹⁷ There is also a growing interest for subject-specific laryngeal models as tools for personalized medical care.¹⁸ Nonetheless, the definition of generic models may be more useful for research applications, especially when investigating general phonation phenomena. Laryngeal cartilage standard models are desirable to ensure repeatability and comparability between research groups, and to provide a simple and accessible geometry to be used for simulation analysis. These models also allow the easy manipulation and editing of the structure to conform to the desired research goals. Because all the biomechanically important dimensions are conserved, standard cartilage models can be used for various sorts of simulations, for example, FE modeling of the laryngeal framework or kinematic analysis of the laryngeal cartilages in different postures and its effects on the vocal folds, simulation of swallowing mechanism, and simulation of larynx movement when pronouncing different sounds. Contrary to the subject-specific models, standard models are more easily accessible because they do not require CT scans or MRI data of the subjects.

Vocal tract and vocal folds models

Vocal folds and vocal tract geometries are less complex than those of the laryngeal cartilages. As pointed out earlier, because of the large difference between tissue and air intensity, segmentation of the vocal fold and vocal tract is easier and faster than that of the laryngeal cartilages. As a result, it is more feasible to create human-specific solid models of the vocal tract and vocal folds rather than creating standard models. No attempt was made to create a standard model for vocal folds because vocal folds are soft and their elongation varies in different phonation postures. Vocal fold geometry depends on the mechanical properties of the vocal fold's tissue, the frequency of the phonation, and the posture of the laryngeal framework. That makes the creation of the standard 3D model of the vocal folds less useful.

Limitations of the present study

Performing CT scan is not possible on healthy subjects because of radiation exposure. Therefore, all the reconstructions were performed on existing patient data available in the hospital archive. That hampered the creation of a normative model of a healthy larynx and vocal fold. Unfortunately, no comprehensive pathology information was available for subjects, and that makes the comparison between cases more challenging and limited to the visible features from CT images. The settings of the CT imaging also differ from one subject to another, and that could have affected the comparisons between different cases.

Conclusions

Eight sets of laryngeal cartilages were successfully segmented from CT scan images to recreate human-specific models of the laryngeal cartilages, vocal folds, and vocal tracts. The morphometric measurements from the reconstructed laryngeal cartilages were compared with those from excised larynges and deemed to be accurate within a comparatively small relative error. Healthy and postsurgery geometries of vocal folds and vocal tract during phonation and respiration were also reconstructed from CT images. To enhance the repeatability and comparability between research groups and also to facilitate the access to the 3D models, a generic standard model of the laryngeal cartilages was proposed. Cartilage standard models were designed using landmark points and dimensions from the reconstructed geometries. Biomechanically important morphometric features were preserved in these models making them ready for further simulations. Human-specific solid models for vocal folds and vocal tract are easily obtained owing to the fact that their segmentation is

much easier than that of the cartilages. The fact that the geometry of the vocal folds constantly changes makes the concept of a standardized vocal fold less useful.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix: Design details of laryngeal cartilages and engineering drawings

The thyroid cartilage was constructed in two parts, namely the cornua and the laminae. Each part was created on one side and mirrored across the midsagittal plane. The cornua were designed using ellipses sketched parallel to the coronal plane. Their major and minor diameters were averaged from the reconstructed geometries, and their positions were given according to those dimensions from Table 1. All measurements were referenced and adapted to the inferior-posterior edge of the thyroid notch (point 2 in Figure 2A). The lamina was constructed using four sketches also parallel to the coronal plane. Sketch details can be found in Figure A1. To enhance the realism of the cartilage, particular attention was placed on ensuring the correct curvature of the superior edge of the lamina, including that of the thyroid notch. However, because these cartilages are aimed at uses relating to phonation phenomena, less emphasis was given to the oblique line, where the thyrohyoid muscles attach to the thyroid. Because the hyoid bone has only a minimal role in voice production, it was not included in this model. The various parts of the thyroid were lofted together as surfaces before being converted to solid bodies.

The cricoid cartilage was the simplest of the three structures to construct, created from a single loft of four sketches and two splines. Two sketches were made on the midsagittal plane and two others on the coronal plane. In particular for this cartilage, great importance was placed on joint facet locations. The cricothyroid facets were delimited simply by the dimensions of the coronal plane sketches and the cricoarytenoid facets by the superior spline. The superior spline connects the top edges of all sketches and delimits points X (left and right), 8–8, and 6–6. The inferior spline emphasizes the anterior arch, points 9–9 and 7–7. Construction details are shown in drawing shown in Figure A2.

The arytenoid was composed of six sketches lofted together using three splines. A larger amount of sketches was necessary to ensure correct thickness and shape. As discussed in the Section “Comparisons between morphometric measurements obtained from 3D solid models and cadaver data,” the dimensions of the reconstructed arytenoids were subject to large errors, especially those dimensions involving the vocal process. Therefore, to minimize the error in the generic model, measurements involving the exact location of the vocal process were taken from literature values. The arytenoids were constructed at an angle of 51.84° from the midsagittal plane, and at a height of 25.05 mm from the top plane to make the final assembly easier. Drawing shown in Figures A3 and A4 show the important characteristics of the structure. The 3D standard cartilages models are shown assembled in Figure A5.

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Figure 1. Three-dimensional reconstructed laryngeal framework from computed tomography scan data. (A) Thyroid. (B) Cricoid. (C) Arytenoid. (D) Laryngeal cartilage framework.

Figure 2. Measurements definitions and landmarks: (A) Thyroid. (B) Cricoid. (C) Arytenoid.

Figure 3. Cross-section view of three-dimensional reconstructed vocal tract. (A) Healthy larynx before smoothing. (B) Healthy larynx after smoothing. (C) Postsurgery larynx.

Figure 4. Healthy larynx. (A) Vocal tract model. (B) Corresponding sagittal view.

Figure 5. Postsurgery larynx. (A) Vocal tract model. (B) Corresponding sagittal view.

Figure 6. Complete vocal tract. (A) Three-dimensional solid model. (B) Corresponding sagittal view.

Table 1
Comparison of the Morphometric Features of Three-Dimensional Reconstructed Model With Tayama et al¹ for Thyroid Cartilage

Thyroid	Experimental			Tayama et al ¹		
	Mean	SD	Num	Mean	SD	Diff%
Superior cornua, left to right (A-A)	37.55	7.30	6	35.5	7.75	5.79
Superior to inferior cornua, left (A-B)	47.17	3.87	6	46.38	4.58	1.70
Superior to inferior cornua, right (A -B)	45.22	7.90	7	43.07	7.37	4.98
Left to right width of posterior edges, midvertical (1-1)	44.47	4.02	7	41.65	2.82	6.77
Anterior thyroid notch to inferior border (D-D)	19.77	1.59	7	19.24	0.79	2.75
Superior thyroid seam thickness (D -C)	3.69	0.60	7	4.13	0.38	10.65
Inferior thyroid seam thickness (D-2)	3.32	0.43	7	3.68	1	9.89
Anterior to posterior length, bottom (inside 2-2)	27.30	1.59	7	29.7	4.62	8.08
Inferior cornua, left to right (B-B)	31.33	3.27	7	34.8	4.06	9.97
Laryngeal prominence to posterior edges (C-C)	34.32	1.37	7	37.27	4.52	7.91
Angle between thyroid laminae ()	64.51	7.70	7	77.17	10.15	16.41
Angle between seam and cornua ()	34.96	3.20	7	35.22	3.46	0.75
Average percent difference						7.14

Abbreviations: Num, the number of models associated with each measurement; SD, standard deviation.

Table 2
Comparison of the Morphometric Features of Three-Dimensional Reconstructed Model With Tayama et al¹ for Cricoid Cartilage

Cricoid	Experimental			Tayama et al ¹		
	Mean	SD	Num	Mean	SD	Diff%
Anterior arch, superior-inferior height (I-I)	7.28	2.21	8	7.05	1.02	3.25
Anterior arch, anterior-posterior thickness (midheight, G)	3.53	0.80	8	3.16	0.72	11.86
Posterior wall, superior-inferior height (F-F)	27.47	3.40	8	22.69	1.68	21.05
Posterior wall, left to right width (at CT facets, 5-5)	30.99	4.51	8	29.86	2.59	3.78
Inside diameter, anterior-posterior (cranial edge, 6-6)	30.90	2.12	8	29.36	2.87	5.24
Inside diameter, anterior-posterior (caudal edge, 7-7)	21.78	2.55	8	20.44	2.67	6.56
Inside diameter, left to right (cranial edge, 8-8)	18.11	2.13	8	18.26	1.23	0.80
Inside diameter, left to right (caudal edge, 9-9)	21.10	2.40	8	22.38	1.43	5.73
Cricothyroid articular facet, major diameter (1-2)	6.14	0.23	4	6.15	1.12	0.18
Cricothyroid articular facet, minor diameter (3-4)	4.99	0.15	4	4.73	0.72	5.59
Cricoarytenoid articular facets, major diameter (J-M)	7.28	0.65	6	8.04	0.74	9.43
Cricoarytenoid articular facets, minor diameter (O-N)	4.01	0.40	6	4.07	0.36	1.38
Average percent difference						6.24

Abbreviations: Num, the number of models associated with each measurement; SD, standard deviation; CT, computed tomography.

Table 3
Comparison of the Morphometric Features of Three-Dimensional Reconstructed Model With Tayama et al¹ for Arytenoid Cartilage

Arytenoid	Experimental			Tayama et al ¹		
	Mean	SD	Num	Mean	SD	Diff%
Vocal process to muscular process (R-S)	12.90	0.91	6	15.53	1.23	16.96
Vocal process to apex (R-Q)	16.31	1.18	6	17.51	2.08	6.85
Muscular process to apex (S-Q)	17.45	1.25	6	18.03	1.12	3.24
Cricothytenoid facet, major diameter (W-V)	6.31	0.37	6	6.05	0.44	4.32
Cricothytenoid facet, minor diameter (T-U)	5.07	0.50	6	5.87	0.47	13.71
Vocal process to cricothytenoid facet center (R-X)	8.72	1.31	6	12.36	1.36	29.74
Muscular process to cricothytenoid facet center (S-X)	5.28	0.75	6	5.18	1.13	1.95
Apex to cricothytenoid facet center (Q-X)	14.83	1.31	6	14.84	1.4	0.09
Average percent difference						9.57

Abbreviations: Num, the number of models associated with each measurement; SD, standard deviation.