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LARYNGOLOGY

Three-dimensional imaging of vocalizing larynx by ultra-high-resolution computed tomography

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Abstract

Purpose Ultra-high-resolution computed tomography (UHRCT) is an emerging imaging technology that is able to achieve simultaneous 160 slices with super-thin 0.25 mm thickness. The purpose of this study was to assess the feasibility of UHRCT to visualize laryngeal structure and kinetics.

Methods Three normal volunteers and three patients with unilateral vocal fold paralysis (UVFP) were incorporated in this case series. First, images were taken under five conditions in normal volunteers. Five tasks consisted of (1) air inspiration through the nose (IN), (2) breath holding (BH), (3) sustained vowel /i:/ phonation (IP), (4) humming phonation (HP), and (5) forced glottic closure during exhalation (FC). Three-dimensional CT images of arytenoid and cricoid cartilages, as well as virtual laryngoscopic images, were reconstructed using UHRCT data. Reconstructed images were compared among five conditions to assess the best tasks to picture laryngeal kinetics. Second, pre- and post-phonosurgical images were examined in UVFP patients to evaluate potential role of UHRCT to assess laryngeal pathology in hoarse patients.

Results Among the five conditions, IN and IP conditions were considered suitable to visualize laryngeal structure at rest and during phonation, respectively. Kinetic abnormalities including asymmetric motion of arytenoid cartilages were elucidated in UVFP patients, and virtual endoscopy visualized the clinically invisible posterior three-dimensional glottic chinks. Furthermore, UHRCT was useful to understand changes in laryngeal structure achieved by phonosurgery.

Conclusions UHRCT is an emerging imaging technology that can be used for minimally invasive visualization and assessment of laryngeal structure and kinetics. Future studies to assess more number of patients with laryngeal dysfunction are warranted.

Keywords Ultra-high-resolution computed tomography · Unilateral vocal fold paralysis · Laryngeal imaging · Virtual endoscopy · Three-dimensional reconstruction

Introduction

The function of the larynx and the movement of the vocal folds have been evaluated by means of various imaging procedure, such as flexible laryngeal fiberscopy, videostroboscopy, computed tomography (CT) and magnetic resonance imaging (MRI). In the field of laryngology, the advantages of 3D reconstruction to provide 3D CT imaging for precise clinical diagnoses have been reported in multiple studies [1-8]. Although 3D CT imaging has such advantages, quality of reconstructed images used for diagnoses highly depends on the resolution of original images captured by CT scanning.

Recent improvement in imaging technology introduced ultra-high-resolution computed tomography (UHRCT). UHRCT has smaller detector element and X-ray tube focus size compared with those of conventional CT, to obtain simultaneous 160 slices with super-thin 0.25 mm thickness. Thus, this novel imaging technology could provide better image quality compared with conventional CT imaging. In UHRCT, artifacts are considered negligible due to improved spatial resolution and high-speed data acquisition [9, 10].

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Application of UHRCT with such advantages is reasonable, considering the complicated configuration and kinetics of larynx. However, application of this next-generation imaging technology to visualize laryngeal structure has not been reported.

The purpose of this study was to assess the feasibility of UHRCT for visualizing laryngeal structure and laryngeal kinetics in future clinical settings.

Materials and methods

Subjects and imaging conditions

Three male volunteers (three of the authors, M.M., I.W. and K.S.), who had no history of laryngeal diseases, were assessed to determine the proper conditions to visualize laryngeal kinetics. Their ages ranged between 32 and 48 years (mean, 41.3 years).

Images were taken under five conditions. Five tasks consisted of (1) air inspiration through the nose (IN), (2) breath holding (BH), (3) sustained vowel /i:/ phonation (IP), (4) humming phonation (HP), and (5) forced glottic closure during exhalation (FC). Similar to conventional CT, volunteers lay down on a bed in the supine position and extended their neck using a pillow, and the head was immobilized. Obtained images were reconstructed to visualize the 3D images of arytenoid and cricoid cartilages. Furthermore, virtual laryngoscopic images were also reconstructed.

Laryngeal images of three patients with unilateral vocal fold paralysis (UVFP) were evaluated afterward. Ages of the patients ranged between 70 and 87 years (mean, 78.3 years), and the images were taken under IN and IP conditions.

This study was approved by the institutional review board of Kyorin University School of Medicine (approval #1212), and written informed consent was obtained from all the participants who underwent UHRCT in this study.

CT scanning procedures

The UHRCT scanner was a 160-row multi-detector CT scanner (Aquilion Precision™; Canon medical Systems Corporation, Tochigi, Japan). The UHRCT scanner has three operating options including normal resolution (NR) mode, high-resolution (HR) mode, and super-high-resolution (SHR) mode. Laryngeal images were evaluated using SHR mode in this study. The detector matrix of the UHRCT is 1792 detector channels × 160 rows, and the size of each element is 0.25 × 0.25 mm reconstruction in hybrid iterative reconstruction (Adaptive Iterative Dose Reduction 3D, Enhanced Strong). The beam collimation is 0.25 mm × 160 rows. The scanning parameters were set as follows: tube voltage, 120 kVp; noise index, 13 Hounsfield units (HU) for 0.25 × 0.25 mm through automatic exposure control, the CT Hounsfield unit is calibrated such that the standard deviation in scanning range of 2 mm was 13; helical pitch, 0.569; rotation time, 0.5 s per rotation; and X-ray focus size, 0.6 × 1.3 mm. The UHRCT matrix size is 1024 × 1024, slice thickness is 0.25 mm, and slice interval is 0.2 mm. In this study, the scanning time from nasopharyngeal level to subclavicular level was approximately 4.0 s. When scanning was limited to larynx only, from upper horn of the thyroid cartilage to the lower margin of the cricoid cartilage, scanning time was shortened to approximately 1.0 s. Thus, this UHRCT application was suitable for hoarse patients with short Maximum Phonation Time (MPT).

All data were transferred to a dedicated workstation (Ziostation, version 2.4; Ziosoft, Inc., Tokyo, Japan), followed by data reconstruction into three-dimensional and virtual endoscopic images. The density value for extracting the arytenoid and cricoid cartilage was determined from thin sliced images. A volume rendering technique was used for reconstruction of virtual endoscopy. Total time required to reconstruct the 3D images of cartilages and virtual larygoscopic images in two condition (IN and IP) of one UVFP patient was approximately 20 min.

Results

Three-dimensional reconstruction of laryngeal cartilages and virtual laryngoscopy in normal volunteers

Arytenoid and cricoid cartilages were reconstructed using the UHRCT images taken in five conditions (Fig. 1). Reconstructed images could be freely rotated in the software, and typical assessments were performed using antero-posterior view, and cranio-caudal view of reconstructed cartilages. Bilateral apexes and vocal processes of arytenoid cartilages were visualized to locate at the widely opened position in IN condition (Fig. 1a). On the other hand, arytenoid cartilages were located at adducted position in BH, IP, HP and FC conditions (Fig.1b, e). Furthermore, dynamic morphological changes of larynges were assessed using reconstructed virtual endoscopic images to determine the proper tasks to visualize laryngeal kinetics using UHRCT (Fig. 2). IN condition consistently visualized the laryngeal structure in resting position (Fig. 2a). While BH and FC conditions visualized the antero-posterior compression (APC) of laryngeal structure (Fig. 2b, e), IP and HP conditions visualized the adduction of the vocal folds similar to vocalizing larynx observed under clinical laryngoscopy (Fig. 2c, d). Further discussions with radiological technicians concluded that IP condition was simpler and easier for hoarse patients compared with

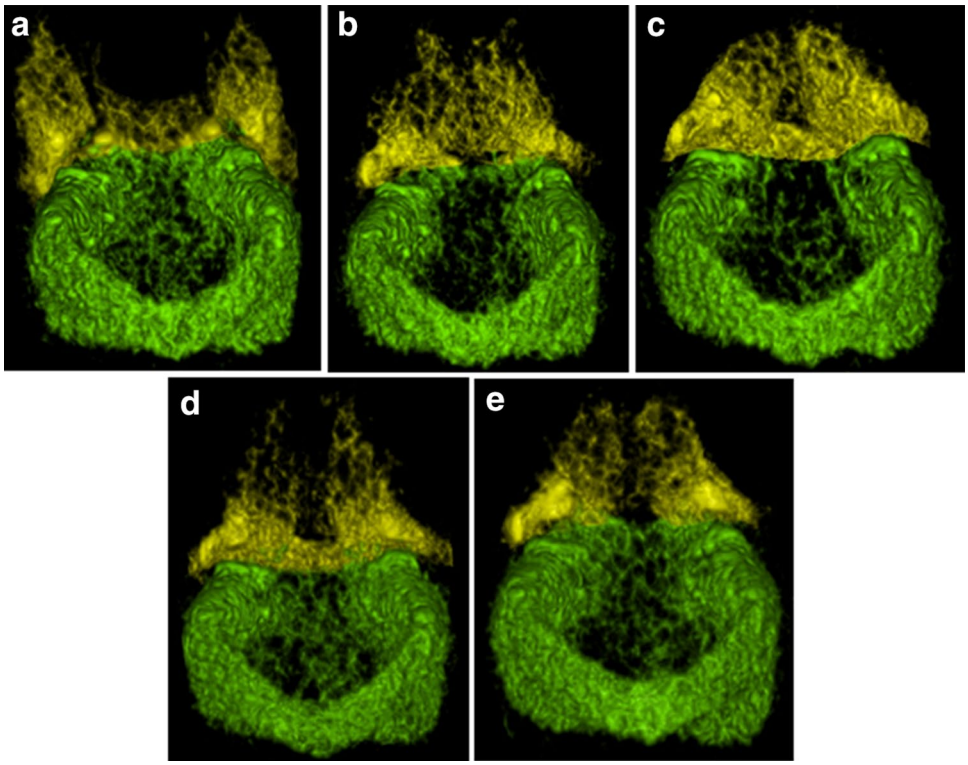

Fig. 1 Three-dimensional reconstruction of arytenoid (yellow) and cricoid (green) cartilages using the UHRCT data. Images of a healthy volunteer are shown. Cranio-caudal views of reconstructed cartilages are shown. Bilateral apexes and vocal processes of arytenoid cartilages were visualized to locate at the widely opened position in IN condition (**a**). On the other hand, arytenoid cartilages were located at adducted position in BH (**b**), IP (**c**), HP (**d**) and FC (**e**) conditions

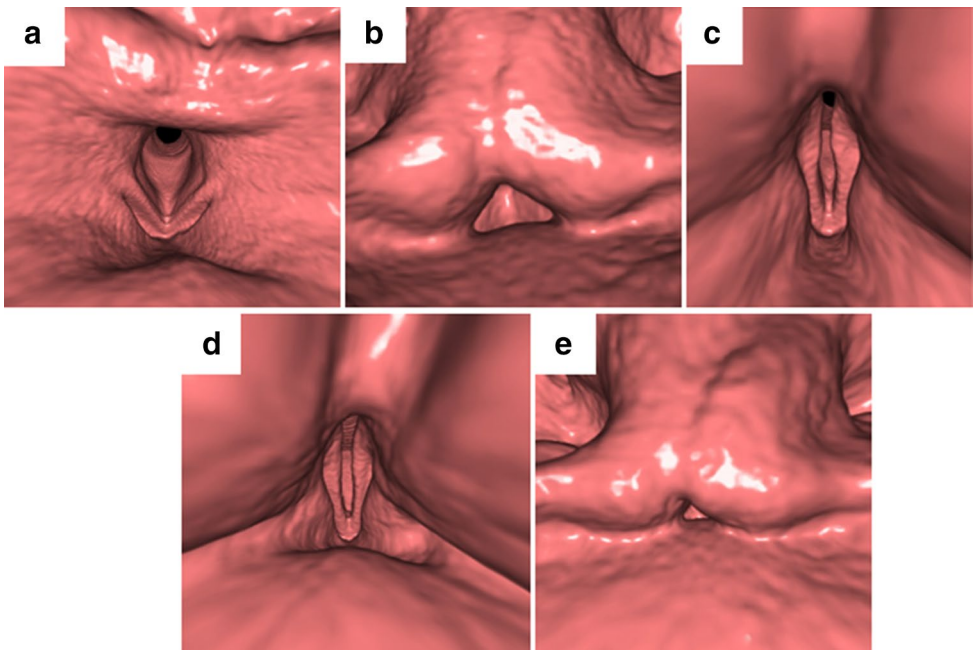

Fig. 2 Virtual laryngoscopic images reconstructed using UHRCT data. Images of the same healthy volunteer as shown in Fig. 1 were taken under five conditions of IN (**a**), BH (**b**), IP (**c**), HP (**d**), and FC (**e**)

HP condition. Thus, IN and IP conditions were adapted to examine larynx in resting position and during phonation, respectively. Although both BH and IP conditions induced APC of laryngeal structure (Fig. 2b, e) as mentioned above, less severe APC was observed in BH condition compared with FC condition. Furthermore, in BH condition (Fig. 1b), arytenoid cartilages were located at adducted position similar to IP condition (Fig. 1c). Thus, BH condition was adapted as a reliable substitute for IP condition in the patients with difficulties to sustain the vowel "i" during CT capturing.

UHRCT imaging of diseased larynx with UVFP

One representative example of the endoscopic (Fig. 3a, b) and UHRCT images (Figs. 3c–e, 4, 5) in a patient with left UVFP is shown. He was a 78-year-old man who suffered left UVFP after surgery for an aortic aneurysm.

In the flexible endoscopic view, the arytenoid hump on the paralyzed side (left) was displaced anteriorly, and left vocal process was invisible (Fig. 3a). Furthermore, vocal folds were completely invisible during phonation due to over-adduction of supraglottic structure (Fig. 3b). In virtual endoscopic images, left vocal process was visualized to locate in paramedian position at rest (IN condition) (Fig. 3c). Vocal folds were still hardly visualized in IP condition when tip of the virtual endoscope was set above arytenoids (Fig. 3d). However, both horizontal and vertical gaps of bilateral vocal processes during phonation were observed when tip of virtual endoscope was set lower beyond the left arytenoid hump (Fig. 3e). This three-dimensional gap of bilateral vocal processes was clearly visualized in the 3D reconstructed laryngeal cartilages in IP condition (Fig. 4a, b). Simultaneous arytenoid adduction and thyroplasty type I were performed on this patient. Postoperative UHRCT images proved the positional change of left arytenoid cartilage to phonatory position (Figs. 4c, d, 5). Furthermore, 3D gap of bilateral vocal process was not observed during phonation in UHRCT imaging after surgery (Figs. 4c, d, 5b).

Radiation exposure

The median radiation dose of larynx with UHRCT was 0.8 mSv. We calculated the radiation dose using k-factor of ICRP [11].

Discussion

Multiple diagnostic procedures including electroglottography, video laryngoscopy, videostroboscopy, high-speed imaging, electroglottography, CT, and MRI have been utilized to visualize and evaluate the stereotypic motion and vibration of the vocal fold. Among them, CT is the current gold standard for airway measurements as the air–tissue interface is better delineated by CT scan compared with

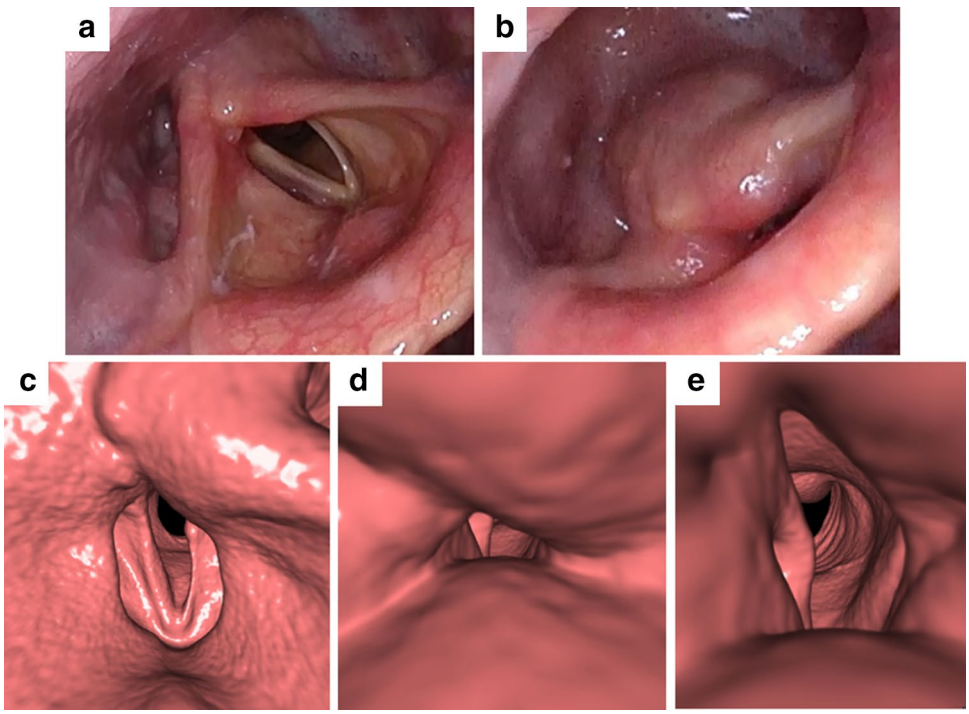

Fig. 3 Flexible laryngoscopic images (**a**, **b**) and reconstructed virtual laryngoscopic images (**c**–**e**) of a patient with left UVFP before phonosurgery. Flexible laryngoscopic images of the patient were taken at rest (**a**) and during phonation (**b**). UHRCT images were taken under IN condition (**c**) and IP condition (**d**, **e**). Paralyzed left arytenoid hump was displaced anteriorly at rest, and left vocal process was invisible under flexible endoscope (**a**). However, rotatable virtual laryngoscopic image could visualize the paralyzed vocal process located in paramedian position (**c**). Vocal folds were invisible during phonation due to over-adduction of supraglottic structure under flexible endoscope (**b**). IP task also induced severe APC, and vocal folds were hardly visualized when the tip of virtual laryngoscope was set above the arytenoid (**d**). However, both horizontal and vertical gaps of bilateral vocal process were clearly visualized when the tip of virtual laryngoscope was set under arytenoid hump (**e**)

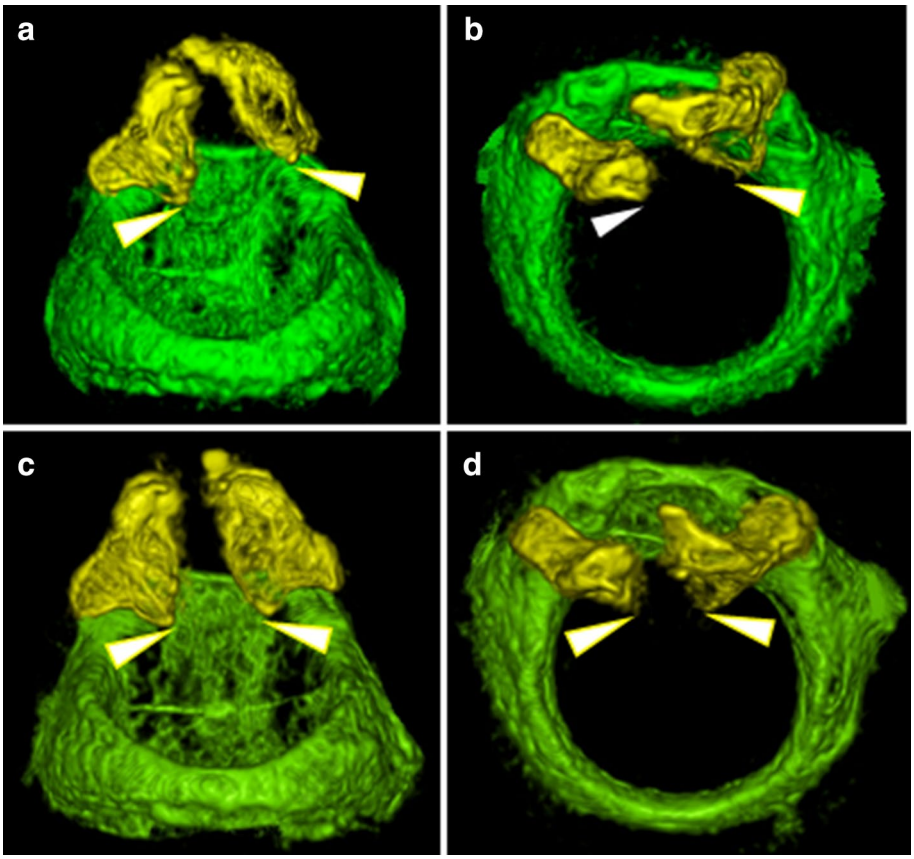

Fig. 4 Three-dimensional reconstruction of arytenoid (yellow) and cricoid (green) cartilages in the same patient as shown in Fig. 3. Images were captured under IP condition, and antero-posterior views (**a**, **c**) and cranio-caudal views (**b**, **d**) of reconstructed cartilages are shown. Paralyzed left arytenoid cartilage located superoposterior to non-diseased side before phonosurgery (**a**, **b**). Simultaneous arytenoid adduction and thyroplasty type I were performed on this patient. Left arytenoid cartilage was adjusted to phonatory position, and 3D gap of bilateral vocal process was not observed during phonation after surgery (**c**, **d**). Arrowheads, vocal processes

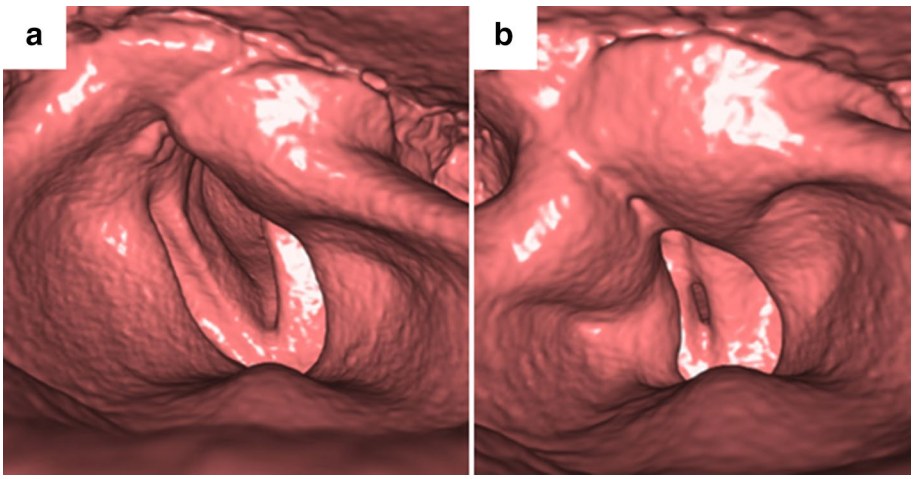

Fig. 5 Post-operative virtual laryngosopic images of the same patient as shown in Figs. 3 and 4. Surgical procedures adjusted the position and volume of diseased vocal fold (**a**, IN condition). Furthermore, posterior glottic chink and APC were not observed in IP condition (**b**)

MRI [2, 12]. Yumoto et al. [3] were the first to depict the laryngeal structures in three dimensions using helical CT images. Phonating and inhaling conditions were used for 3D assessment of vocalizing larynx in Yumoto's studies [3, 4, 13]. Their scanning time was 5 s to include most of laryngeal structures [4, 13]. Jun BC et al. used functional 3D CT to assess laryngeal structure during phonation, and they required the patients with UVFP to phonate 10 s for laryngeal imaging [2]. However, patients with UVFP represent MPT of less than 5 s very often. Recently, UHRCT achieved the super-fine visualization of human anatomy with short scanning time [9, 10]. The lower margin of scanning area was set at the subclavian level, and the higher margin was set at nasopharyngeal level to determine the proper conditions to examine laryngeal kinetics in this study. Scanning time required to obtain the image between these levels using UHRCT was less than 4 s. Furthermore, scanning time could be shortened to approximately 1.0 s when scanning was

limited to larynx only. This short scanning time successfully achieved the assessment of laryngeal kinetics in all three patients with UVFP whose MPT were 2–3 s (mean, 2.7 s).

In this study, vertical and horizontal gaps between bilateral vocal processes could be evaluated using UHRCT in the patients with UVFP. Thus, this novel imaging technology was helpful to determine proper surgical procedure based on the individual pathology of the patient. Furthermore, significant changes of laryngeal structure were clearly observed in a patient with UVFP after phonosurgery to achieve proper cartilage repositioning for successful vocalization.

Additionally, visual assessment of false vocal fold, ventricle, arytenoid hump, aryepiglottic fold, and tracheal rings were also possible using virtual endoscopy suggesting further potential of UHRCT for airway management.

However, the present study has limitations. As this study incorporated a small subject sample size, future studies should include more number of patients with valuable laryngeal diseases to assess further potential of UHRCT to evaluate the patients with vocal problems.

Conclusion

UHRCT is an emerging imaging technology that can be used for minimally invasive visualization and assessment of laryngeal structure and kinetics. IN and IP conditions were considered reasonable to obtain images of larynx at rest and on vocalization, respectively. 3D reconstruction of UHRCT images achieved the positional assessment of bilateral arytenoid cartilages in UVFP. Virtual endoscopy was helpful to understand the pathology of the diseased larynx. Furthermore, UHRCT was useful to understand changes in laryngeal structure achieved by phonosurgery. Future studies to assess more number of patients with laryngeal dysfunction are warranted.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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