ORIGINAL ARTICLE

Novel airway-cartilage combined model for medialization laryngoplasty and laryngotracheal reconstruction surgery planning

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Abstract

Background: The clinical outcomes of surgical treatments for vocal cord paralysis and tracheal stenosis, such as medialization laryngoplasty and laryngotracheal reconstruction, vary owing to the complex anatomy and physiology of the human upper airway. However, advances in three-dimensional (3D) simulation and printing ushered its use on an office-based workstation to aid in several surgical areas.

Methods: The preoperation neck computed tomography image was loaded into the InVesalius 3.0 software for manual segmentation of airway and nearby important anatomic landmarks including hyoid bone, thyroid cartilage, and cricoid cartilage. The 3D model of the desired anatomy structure was manufactured and used for presurgical planning and rehearsal of the surgery.

Results: We review cases of four patients: two cases of unilateral vocal palsy undergoing medialization laryngoplasty and two cases of tracheal stenosis patients who used the air-cartilage combined model

Conclusion: Preoperation planning of the medialization thyroplasty could be more precise by prevision of the paralyzed vocal cord plane. Tracheal surgery could benefit from a preoperative design of segmented length. The novel airway-cartilage combined model offers new insight into vocal cord and trachea surgery.

Keywords: 3D Printing; Larynx; Medialization laryngoplasty; Trachea

1. INTRODUCTION

Advances in fabrication technology and software development made three-dimensional (3D) printing much more accessible in recent years. Currently, 3D printing is being used in the medical field for the simulation of surgical anatomy,[1,2] tissue and organ fabrication,[3] and the creation of customized implants and prosthetics,[4] thereby expanding its avenues in the areas of neurosurgery,[5] plastic and reconstructive surgery,[6] oral maxillofacial surgery,[7] and otolaryngology.[8] Emerging trends in simulation-based planning for otolaryngology and endolaryngeal surgery can improve surgical performance and help shorten the learning curve.[1,2,9] The ability of 3D printing models to conceptualize complex anatomy of different components within a single model, such as the respiratory airway, cartilage, and bone, endorse its role as an important learning tool, besides serving as a platform to aid the diagnosis and treatment of different disorders.

Medialization laryngoplasty is an effective surgery to restore glottic insufficiency in paralyzed vocal cords, and a comprehensive understanding of the laryngeal anatomy and physiology is essential to obtain satisfying results for the target organ, the vocal cord, which is hidden in the whole surgical field. Furthermore, Desuter et al[10] reported that the anatomy of the thyroid cartilage varies between patients; a significant difference is found in the laminar angle of the thyroid cartilage between males and females, which underscores the need for individualized evaluation of prosthesis design. Anderson et al[11] reported that 33% of patients undergoing a primary type I thyroplasty required a secondary surgical procedure, while 9.4% of the patients needed implant removal or repositioning. The most important factor contributing to these challenges was the inability to visualize the structures (vocal cord level, arytenoid cartilage, and the actual airway condition), which were positioned behind the thyroid cartilage lamina during laryngeal framework surgery. Therefore, a need exists for a different technique for better-customized evaluation of the airway and thyroid cartilage during laryngeal reconstruction surgery.

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Laryngotracheal resection is the cure for multiple laryngotracheal diseases including postintubation tracheal stenosis, tracheal tumor, tracheoesophageal fistula, tracheobronchomalacia. However, some anastomotic complications (~9%) and a 1% incidence of postoperative mortality had been reported.[15] Nakache et al[16] reported a 29.5% of revision rate after primary laryngotracheal resection surgery with a decannulation rate increased to 88.5% after revision surgeries. Additionally, many surgeons are still deterred from adapting this procedure because of a steep learning curve. Therefore, a better preoperative evaluation tool is warranted for easier treatment planning and designing a surgical plan.

Accordingly, this study aimed to demonstrate our experience in utilizing a 3D printed air-cartilage combined model for preoperation evaluation of complex laryngeal anatomy. The 3D model provided a direct and intuitive way for preoperation evaluation and design of medialization laryngoplasty surgery and laryngotracheal reconstruction.

2. METHODS

This is a retrospective review of four patients who received medialization laryngoplasty or laryngotracheal reconstruction surgery by the authors. All patients underwent a head and neck computed tomography (CT) examination (with contrast medium, thickness of 1 mm) as part of a presurgical evaluation. Anatomical data obtained from the head and neck CT were stored as "digital imaging and communications in medicine" (DICOM) images. The images were loaded into InVesalius 3.0 (Centro de Tecnologia da Informação Renato Archer, Brazil), a freely available software, for manual segmentation of airway and important adjacent anatomic landmarks including the hyoid bone, thyroid cartilage, and cricoid cartilage. The airway was segmented with a threshold of −200 to −600, and the cartilage and bones were segmented with a threshold of 90 to 3000. The airway could be readily delineated since the soft tissue (e.g., fat) had HU number between −50 and −100 and the air had an HU number of −1000 and less. Thus, a transition from −200 to −600 HU could be identified as a transition zone from the finest soft tissue to the air. By segmenting this transition zone, a thin smooth mesh covering the surface of the airway in the larynx could be obtained. The thyroid cartilage and the arytenoid cartilage could also be section in there ossifying part. For those not calcified enough to perform threshold segmentation, manual selection of the desired part of the cartilages on the CT image was performed to obtain the correct model. While the tip of the vocal process could not be 100% located by the CT image alone for its small in size and not well calcified, the actual vocal process would be expected to be an elongation of what we sectioned through CT image. Thus, we can still approximate the vocal process plane by viewing the underestimated vocal process on the result model and suggest the position for the implant installation. Surface rendering was performed, and the desired mesh was output as a single-layer mesh, which was then saved as a binary stereolithography (STL) file.

The STL files were imported into the Autodesk Meshmixer software (Autodesk Inc.) for designating the landmarks or windows and marking the desired vocal cord plane and arytenoid cartilage vocal process location on the model for direct visualization of the glottic airway morphology (Fig. 1). To design the thyroid cartilage window, the exact size and position of the window vary according to different size of the thyroid cartilage. Most of the time, the anterior border was 5 to 7 mm posterior to the midline, the inferior border was 5 mm superior to the inferior border, the window's width was 10 to 12 mm with the height 4 to 6 mm in size. The angle of the thyroid window was designed according to the projected plane from the vocal cord plane as performed in Fig. 1A. Thus, a prefabricated position of thyroid cartilage window could be obtained to maximize the contact of vocal cord plane and implant. The time needed from acquiring the CT-DICOM file to completing the model design was around 1 to 6 hours depending on CT image quality and the complexity of anatomical structures.

For further fabrication, we used the fused filament fabrication 3D printer Flashforge Creator Pro (Zhejiang Flashforge 3D Technology Co., Jinhua City, China) with high-resolution 3D printed material—1.75 mm polylactic acid. The printing time varied depending on the size and the material density settings. Models involving only the larynx took around 4 to 6 hours, while other models, which involved larger areas, took more than 24 hours.

The customized patient-specific 3D models were brought to the medical staff team for preoperation rehearsal, allowing for a detailed examination of the length, morphology, and intervention strategy.

The study was approved by the Institutional Research Board of Kaohsiung Veterans General Hospital (KSVGH21-CT6-12). Herein, we will present four examples of utilizing airway-cartilage combined model to aid in medialization laryngoplasty and laryngotracheal reconstruction surgery planning.

3. RESULTS

3.1. Vocal cord projection, the marking method

A 64-year-old female with adenocarcinoma of anterior mediastinum received video-assisted thoracoscopic tumor excision surgery and thymectomy. After the operation, she presented with left vocal cord paralysis and was referred to the Department of Otolaryngology, Head and Neck Surgery, Kaohsiung Veterans General Hospital for further evaluation. Her phonation time was 2.67 seconds with a GRBAS (Grade, Roughness, Breathiness, Asthenia, Strain) scale 33333, and type I thyroplasty was suggested owing to the permanent nature of the nerve lesion. The airway-cartilage combined model was fabricated with the simulation of the vocal cord plane and presurgical localization of vocal cord and arytenoid locations (Fig. 2). The mark was designed by an otolaryngologist representing the vocal cord plane, and the position of the vocal process of arytenoid cartilage was projected onto the ipsilateral thyroid cartilage lamina. By presenting the model in advance to the surgery, the information of actual vocal cord plane was stored in the surgeon's mental design which assisted in designing a suitable window for the silicon block implantation. The surgery was performed under local anesthesia with the thyroid cartilage window designed according to the window designed in the 3D model since both were designed in the same principle. The hand-carved firm silicone block was designed and produced intraoperatively according to the actual thyroid cartilage window on the patient. Intraoperative nasopharyngoscopy had been performed simultaneously to monitor the medialization process to ensure adequate correction of paralyzed vocal cord. All the patients who received medialization laryngoplasty stayed overnight with one negative-pressure drain, which was removed the next morning and the patient may be discharged.

Postoperative follow-up laryngoscopy showed decent medialization of the left vocal cord with no phonation gap. Follow-up phonatory ability test showed significant improvement in all results, especially the smoothed amplitude perturbation quotient (from 15.6% to 3.3%), peak-to-peak amplitude variation (from 27.8% to 8.2%), and amplitude tremor intensity index (from 15.3% to 3.8%). The patient's voice outcome also improved with decreased aspiration events.

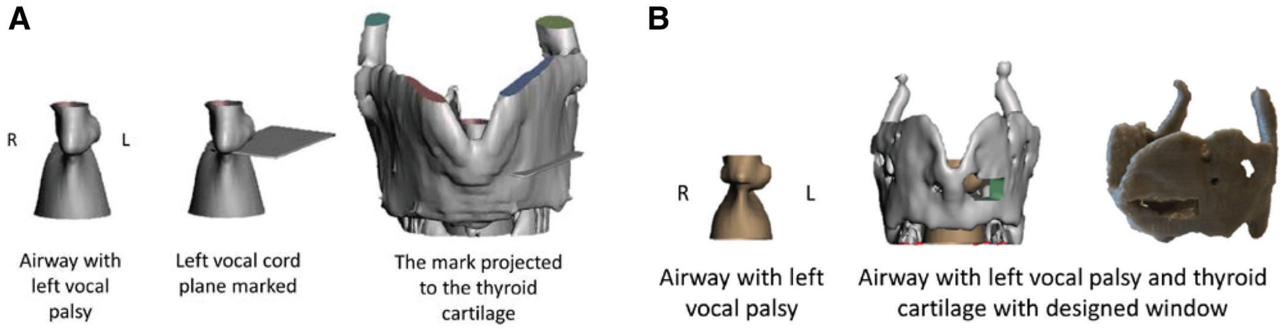

Fig. 1 Illustration of different methods to design air-bone combine 3D model A, Principle of marking vocal cord plane onto thyroid cartilage. B, A premade window design for glottis evaluation.

3.2. Vocal cord projection, the window method

The patient was a 71-year-old male with left cranial nerve-IX schwannoma and developed postoperative left vocal cord paralysis after a far lateral transcondylar approach for tumor removal. He presented with symptoms of easy choking, hoarseness, and nasogastric tube dependence for frequent aspiration pneumonia. Laryngoscopy showed left vocal cord paralysis with phonation gap and saliva pooling at the pyriform sinus bilaterally. Therefore, left type I thyroplasty was suggested. Neck CT showed left vocal cord palsy with intact bilateral arytenoid. The computerized airway-cartilage combined model was designed. However, because the patient had been inserted with a nasogastric tube that entered the esophagus from the left pharyngeal wall resulting a compression effect onto the left arytenoid cartilage, the left arytenoid cartilage was displaced anteriorly as seen in Fig. 2B, which made it unreliable to predict its natural position. Therefore, instead of marking on an ipsilateral thyroid cartilage lamina, we manually designed a window according to

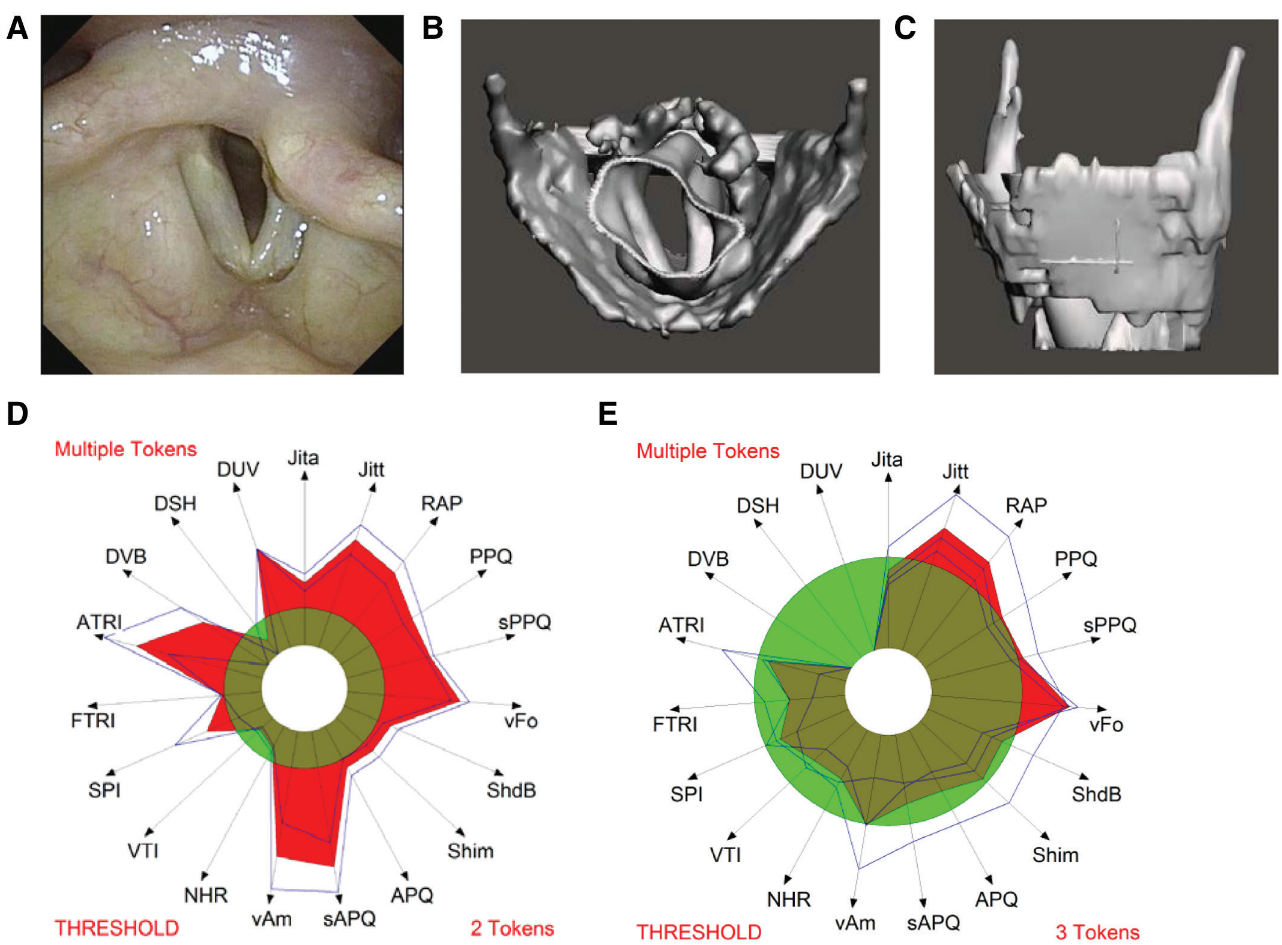

Fig. 2 Air-bone combined 3D printing model of a left vocal palsy patient with vocal cord plane and arytenoid vocal process position marked on left thyroid cartilage lamina A, Laryngoscopy showed left vocal cord palsy. B, Cephalic view of 3D reconstructed airway and cartilage model. C, Oblique view of designed ABC model with a mark shown on left thyroid cartilage alar. D, Presurgery phonation ability test. E, Postsurgery phonation ability test.

Isshiki's method,[17] which allowed direct visualization of the left airway morphology through the thyroid cartilage (Fig. 3). The surgery was performed under local anesthesia, and the actual surgical window was designed posterior to the manually opened airway vision window. After a week of voice resting, the patient's hoarseness improved, and easy choking ceased after the surgery.

3.3. Subglottic stenosis simulation

A 27-year-old male patient was involved in an occupational factory explosion, which resulted in a third-degree burn injury involving >90% of his total body surface area. Prolonged endotracheal tube intubation led to the development of subglottic stenosis after tracheostomy. Neck CT showed a 3.1-cm segmental stenosis over the subglottis, termed as Cotton-Myer grade IV (Fig. 4). A computerized 3D image and the 3D printed model of the laryngotracheal lesion including upper airway, hyoid bone, thyroid cartilage, cricoid cartilage, and tracheostomy tube were created. The 1:1 3D printed model revealed a cylindrical total occlusion of the subglottis starting at 6 mm below the thyroid cartilage's lower border, along with the involvement of 32.5 mm in length and cricoid cartilage airway. Parts of the patient's face and tracheostomy tube were also printed for a more realistic purpose and connection of two disconnected airways (Fig. 4C). The model was used for preprocedural planning, rehearsal, and education of the residents, patients, and the related surgery team. After general anesthesia, segmentation of the trachea including tracheostomy stoma, and partial cricoid cartilage resection, a suprahyoid larynx release with cricotracheal anastomosis was performed. Next, the endotracheal tube was removed 7 days after the operation, and the patient was discharged 21 days after the operation. Follow-up spirometry was continued for 1 month after the operation and it showed moderately severe restrictive ventilator impairment with a forced vital capacity (FVC) of 59.5% and a forced expiratory volume in the first second (FEV1)/FVC of 85.77%. No revision surgery was required, and the patient presented with no sign of restenosis or stridor.

3.4. Trachea stenosis simulation

A 40-year-old male presented with trachea stenosis caused by intubation injury during hospitalization for acute pancreatitis complicated with septic shock and acute respiratory failure. Bronchoscopy exam showed a tracheal stenosis 2 cm below the vocal fold with mature scarring, categorized as Myer-Cotton grade III. The length of stenosis was about 1 cm as estimated from the CT scan (Fig. 5). For airway evaluation, a 3D printed model of the patient's upper airway with thyroid cartilage and cricoid cartilage was made, which revealed stenosis at 6.62 mm below the lower border of the cricoid cartilage with an airway stenosis length of 21.65 mm (Fig. 5C). A small-caliber endotracheal tube (4.5Fr) was inserted, passing through the stenosis airway after general anesthesia and tracheal resection; suprahyoid was released, and an end-to-end anastomosis was performed. The first to fourth tracheal rings were excised (measuring up to 2.5 cm in length) with organized scar formation over the first to third rings. After the surgery, the patient had the chin to chest sutures for 8 days and was discharged from the hospital 13 days after the surgery. The patient recovered well, as evident from the postoperative pulmonary function test, which showed moderately obstructive ventilator impairment with a predicted FVC of 85.6% and FEV1/FVC of 69.91%. The follow-up chest CT exam found a granuloma at the posterior aspect of the upper trachea, which disappeared 12 months later. The characteristics of our two tracheal stenosis cases are summarized in Table 1.

4. DISCUSSION

We discussed two cases each of vocal cord palsy and laryngotracheal stenosis patients who received presurgical evaluation with our airway-cartilage combined model. The models provided an effective way to understand the anatomical structures including airway and cartilage components of the laryngeal box for presurgical evaluation of the vocal cord, arytenoid cartilage, and airway position. The 3D models helped perform a preoperative assessment of the lesion, explain to the patient the procedure to obtain informed consent, and initiate intraoperative discussion for resident education.

Medialization laryngoplasty improves the closure of the glottis and vocal outcomes.[18] Since the surgery was first introduced in 1989, several procedural modifications to expedite the process have been published.[17] Determining the window size and its placement on the thyroid cartilage lamina vary among surgeons due to a fear of fracturing the inferior portion of the thyroid cartilage, yet this may negatively affect the supraglottic vocal tract.[19] The key differences between the original technique and the subsequent modifications were due to changes in the understanding of the physiology and position of the vocal cord plane. Traditional axial images failed to demonstrate the vocal cord plane correctly since the axial plane was usually not parallel to the latter, causing a "mushroom-like" appearance of the vocal cords.[20] Likewise, Hong et al[12] described that the height of paralyzed vocal folds varied depending on the status of the larynx and the appearance of paralyzed arytenoid. Cinar et al[13] reported that the proportion of the distance between the position of the anterior commissure to the superior thyroid notch and the midline of thyroid cartilage varied from 0.5 to 0.28, and the posterior border was found to be at a lower level than the anterior commissure, which may lead to a failed type I thyroplasty. Hiramatsu et al.[14] used 3D CT to evaluate unsatisfactory outcomes after type I thyroplasty and suggested individualized simulation for each case because of the shape difference between left and right thyroid laminas. Eventually, 3D image reconstruction enhanced our understanding of the vocal

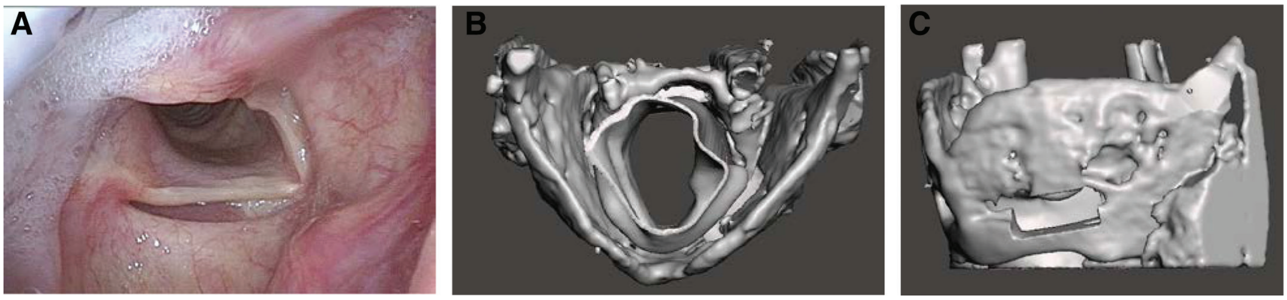

Fig. 3 Presurgery evaluation and design of air-bone combined 3D model. A, Laryngoscopy showed left vocal cord palsy. B, Cephalic view of 3D reconstructed airway and cartilage model with a nasogastric tube compressing left arytenoid cartilage. C, Oblique view of designed ABC model with manually designed window.

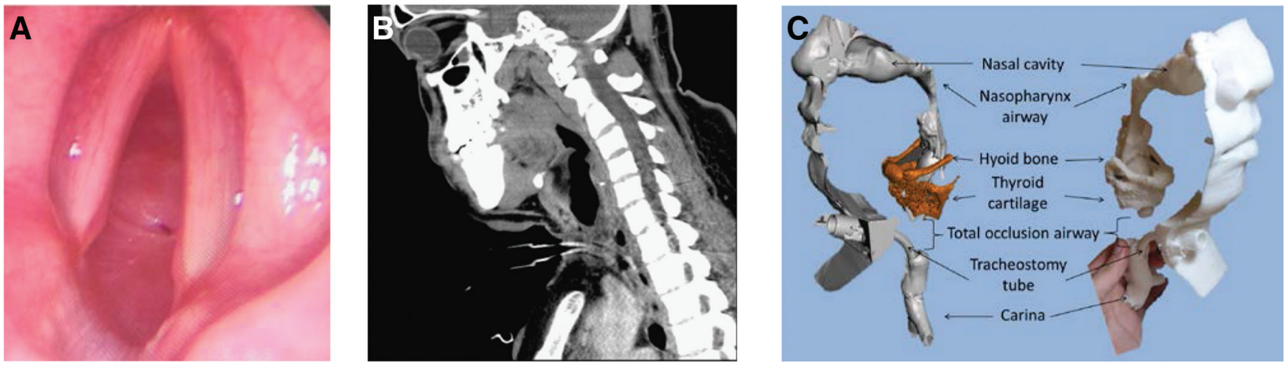

Fig. 4 Subglottic stenosis Cotton-Myer grade IV (A) laryngoscopy, (B) neck computed tomography image. C, Reconstructed 3D model of the upper airway, the hyoid bone, and the thyroid cartilage. The left image is a computer-generated model. The right image is a 3D printed model.

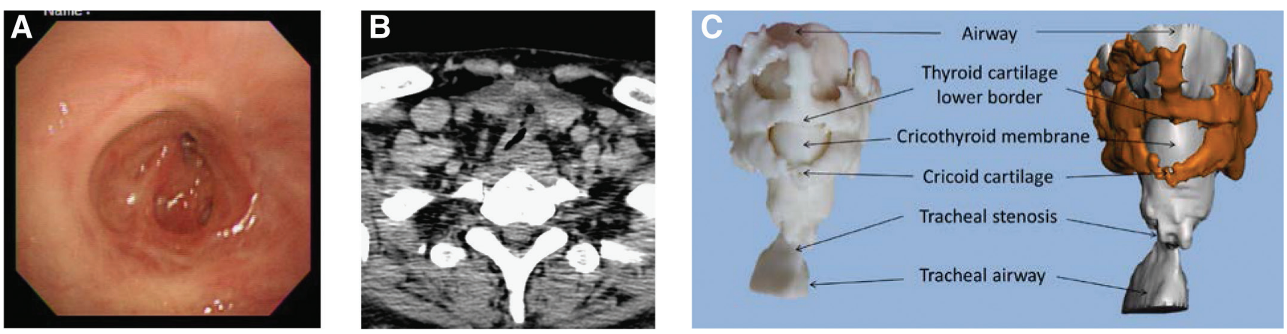

Fig. 5 Trachea stenosis (A) laryngoscopy, (B) chest computed tomography image. C, Reconstructed 3D model of the upper airway thyroid cartilage and cricoid cartilage. Note that the thyroid cartilage was not fully ossified at the upper border and bilateral lamina, which are visible as a defect on the image.

cord plane.[21–23] Bakhshaee et al[24] compared 35 morphometric features of 3D reconstructed model with linear and angular geometric measurements on the thyroid cartilage, cricoid cartilage, and the arytenoid cartilage on dissected larynx after death. The team demonstrated that a 3D CT reconstruction of the human larynx cartilage model was accurate within a small relative error compared to cadaver data. Yumoto et al[25] proposed three types of unilateral vocal fold paralysis glottal configuration models according to different thicknesses and locations of the paralyzed vocal cords with 3D CT images. However, the configuration model required a phonation CT image to classify different patient groups, which was not suitable in routine settings, precluding its applicability. Nevertheless, the configuration model provided pivotal information in raising awareness about the customized treatment of unilateral vocal palsy patients. Hara et al[26] published the outcomes of using 3D CT image to predict vocal cord plane and optimal implant size, which resulted in reducing the operation time by 12 minutes. Our proposed 3D printed models not only provided a direct visualization of glottal configuration in different patients irrespective of the etiology or the severity of vocal cord palsy but also gave crucial information on the arytenoid cartilage's condition, which made patient-tailored medialization laryngoplasty surgery possible.

Table 1

Characteristics of tracheal stenosis study cases

	Patient 4	Patient 5
Age	27	40
Sex	M	M
Stenosis site	Subglottis	Subglottis
Distance from thyroid cartilage, mm	6	20.35
Stenosis length, mm	32.5	21.65
Postoperation LFT		
FEV1 (% predicted)	69.3	72.8
FVC (% predicted)	72	85.6
FEV1/FVC (%)	82.76	70

FEV1 = forced expiratory volume in one second; FVC = forced vital capacity; LFT = lung function test.

Treating subglottic stenosis is challenging due to the narrow subglottic area, which often requires the need to extend the resection to the cricoid cartilage near the vocal cords. Hitherto, laryngotracheal resection with primary end-to-end anastomosis was the definitive curative treatment for benign subglottic stenosis. D'Andrilli et al[27] reported a 99.1% definitive success rate for treating benign stenosis with laryngotracheal resection in their series comprising 109 patients. The restenosis rate was around 4.4% to 9.5% with a dehiscence rate of 0% to 5.5%.[28–30] The risk factors for anastomotic complications were reoperation, diabetes, lengthy resections (≧4 rings), laryngotracheal resections, aged ≤17 years, and the need for tracheostomy before the operation.[15] Therefore, a complete preoperative evaluation is essential for designing a suitable surgical intervention plan and preventing complications. Novel evaluation tools, including CT virtual tracheobronchoscopy with multiplanar reformatting, were introduced in the 2000s, which proved to be an accurate and effective tool for evaluating tracheal stenosis length, grading, localizing, and planning the resection segment.[31–33] In this article, we presented our experience with 3D printing of individual patient models as a new tool for preoperation evaluation. While we believe our 3D printed models had high resemblance with the CT image and actual human larynx, measurement on actual human larynx and counterpart 3D printed model could only be obtained after surgical removal of the larynx itself. Thus, it is not possible to collect this information since total laryngectomy is not in the scope of the current study. Therefore, its accuracy should be further validated in future studies.

Utilizing the 3D printed models in presurgical planning has been successfully practiced in several areas.[5–8] Since the 3D models were synthesized in the actual size of the target organ, the tangible palpability provides surgeons with a better understanding of the complex anatomy of the diseased structure. Traditionally, a rigid or fiberoptic laryngoscopy was the main tool for the evaluation of vocal cord palsy, which was limited in use, since it offered only 2D perceptions of the glottal gap. Meanwhile, a 3D model could provide additional information on arytenoid cartilage position and vocal cord vertical plane on respiration simultaneously. Also, the physical 3D model was exceptional in guiding the residents on where to open the thyroid cartilage window and the potential effects of different implant sizes. The models also offered the patients the opportunity of a better understanding of surgical procedures and the possible risks and benefits of a medialization laryngoplasty.

An emerging role of 3D printing exists with applications in the ear, nose, and throat field for auricular reconstruction framework, treatment of severe acquired tracheomalacia, patient-specific mandible templates, endoscopic sinus surgery, and skull base surgery.[34] Additionally, tracheal surgery benefits from the 3D printed model in complex pediatric tracheal reconstruction,[35] preanesthesia planning per airway morphology after laryngeal cancer surgery,[36] management of tracheobronchial chondromalacia,[37] and as advanced technology to print artificial tracheal graft tissue-engineered tracheal reconstruction.[38] Fiorelli et al[39] used 3D printed airways for endoscopic treatment of upper airway stenosis in seven patients with no complications. Arcieri et al[40] built a 3D model of congenital tracheal stenosis patients aimed to provide a better choice of surgical intervention and improved outcomes. The development of entry-level in-house 3D printing helped in lowering the cost of a patient-specific model to around $90 for each model with an acceptable accuracy (0.54 mm), which made the concept of a patient-specific model feasible and economical.[41] Hsieh et al[42] compared the accuracy of 13 landmarks between 3D models of sinuses and skull base and actual CT data by an image-guided navigation system and stated that the error was less than 1 mm. Also, we achieved comparable results with satisfactory accuracy at a low cost of around $20 per model.

The cases presented in our report should be perused bearing in mind certain important limitations. The main limitation of our study was the accuracy of the vocal cord position in the 3D printed model, since our model could not display dynamic changes of the vocal cord plane between inspiration and phonation. However, unless a thorough electrophysiology exam was performed on laryngeal muscles and documented/corroborated with a CT scan, a precise model representing actual glottic motion was unobtainable. Also, the models lacked soft-tissue information in the paraglottic space rendering the anticipated preoperative implantation planning less accurate compared to actual implantation results. Although the markings representing the vocal cord plane and arytenoid cartilages on the lamina were designed by an otolaryngologist (C.-Y. Huang), further study to validate these landmarks with a human specimen larynx is warranted. Either linear markings or window design to represent vocal cord condition may have been distorted when patients were lying in a chin-tilted position during the surgery.

In conclusion, our airway-cartilage combined model serves as a novel alternative method to visualize the previously unseen airway during laryngotracheal surgery. The models were specific to each patient, despite different etiology of nerve injury causing vocal palsy or any degree of airway injury. This may help otolaryngologists examine the model through different morphology and the impact of the lesion from all previously concealed angles and depths, which potentially aids in preoperative planning. Further study is encouraged to test its reliability and effectiveness with long-term follow-up results.

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REFERENCES

1. Choonara YE, du Toit LC, Kumar P, Kondiah PP, Pillay V. 3D-printing and the effect on medical costs: a new era? *Expert Rev Pharmacoecon Outcomes Res* 2016;**16**:23–32.
2. Guibert N, Moreno B, Hermant C. Usefulness of 3D printing to manage complex tracheal stenosis. *J Bronchology Interv Pulmonol* 2017;**24**:e27–9.
3. Bishop ES, Mostafa S, Pakvasa M, Luu HH, Lee MJ, Wolf JM, et al. 3-D bioprinting technologies in tissue engineering and regenerative medicine: current and future trends. *Genes Dis* 2017;**4**:185–95.
4. Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: a systematic literature review. *Biomed Eng Online* 2016;**15**:115.
5. Randazzo M, Pisapia JM, Singh N, Thawani JP. 3D printing in neurosurgery: a systematic review. *Surg Neurol Int* 2016;**7**(Suppl 33):801–9.
6. Bauermeister AJ, Zuriarrain A, Newman MI. Three-dimensional printing in plastic and reconstructive surgery: a systematic review. *Ann Plast Surg* 2016;**77**:569–76.
7. Lin HH, Lonic D, Lo LJ. 3D printing in orthognathic surgery - a literature review. *J Formos Med Assoc* 2018;**117**:547–58.
8. VanKoevering KK, Malloy KM. Emerging role of three-dimensional printing in simulation in otolaryngology. *Otolaryngol Clin North Am* 2017;**50**:947–58.
9. Wiet GJ, Stredney D, Wan D. Training and simulation in otolaryngology. *Otolaryngol Clin North Am* 2011;**44**:1333–50, viii–ix.
10. Desuter G, Henrard S, Van Lith-Bijl JT, Amory A, Duprez T, van Benthem PP, et al. Shape of thyroid cartilage influences outcome of montgomery medialization thyroplasty: a gender issue. *J Voice* 2017;**31**:245.e3–8.
11. Anderson TD, Spiegel JR, Sataloff RT. Thyroplasty revisions: frequency and predictive factors. *J Voice* 2003;**17**:442–8.
12. Hong KH, Jung KS. Arytenoid appearance and vertical level difference between the paralyzed and innervated vocal cords. *Laryngoscope* 2001;**111**:227–32.
13. Cinar U, Yigit O, Vural C, Alkan S, Kayaoglu S, Dadas B. Level of vocal folds as projected on the exterior thyroid cartilage. *Laryngoscope* 2003;**113**:1813–6.
14. Hiramatsu H, Tokashiki R, Suzuki M. Usefulness of three-dimensional computed tomography of the larynx for evaluation of unilateral vocal fold paralysis before and after treatment: technique and clinical applications. *Eur Arch Otorhinolaryngol* 2008;**265**:725–30.
15. Wright CD, Grillo HC, Wain JC, Wong DR, Donahue DM, Gaissert HA, et al. Anastomotic complications after tracheal resection: prognostic factors and management. *J Thorac Cardiovasc Surg* 2004;**128**:731–9.
16. Nakache G, Primov-Fever A, Alon EE, Wolf M. Predicting outcome in tracheal and cricotracheal segmental resection. *Eur Arch Otorhinolaryngol* 2015;**272**:1471–5.
17. Isshiki N. *Phonosurgery - Theory and Practice*. Tokyo: Springer-Verlag; 1989.
18. Isshiki N. Progress in laryngeal framework surgery. *Acta Otolaryngol* 2000;**120**:120–7.
19. Maragos NE. Type I thyroplasty: pitfalls of modifying the Isshiki approach. How I do it. *J Voice* 1997;**11**:470–3.
20. Paquette CM, Manos DC, Psooy BJ. Unilateral vocal cord paralysis: a review of CT findings, mediastinal causes, and the course of the recurrent laryngeal nerves. *Radiographics* 2012;**32**:721–40.
21. Hewavitharanage S, Gubbi J, Thyagarajan D, Lau K, Palaniswami M. Estimation of vocal fold plane in 3D CT images for diagnosis of vocal fold abnormalities. *Annu Int Conf IEEE Eng Med Biol Soc* 2015;**2015**:3105–8.
22. Oyamada Y, Yumoto E, Nakano K, Goto H. Asymmetry of the vocal folds in patients with vocal fold immobility. *Arch Otolaryngol Head Neck Surg* 2005;**131**:399–406.

23. Yumoto E, Oyamada Y, Nakano K, Nakayama Y, Yamashita Y. Three-dimensional characteristics of the larynx with immobile vocal fold. *Arch Otolaryngol Head Neck Surg* 2004;**130**:967–74.
24. Bakhshaee H, Moro C, Kost K, Mongeau L. Three-dimensional reconstruction of human vocal folds and standard laryngeal cartilages using computed tomography scan data. *J Voice* 2013;**27**:769–77.
25. Yumoto E, Sanuki T, Minoda R, Kumai Y, Nishimoto K. Glottal configuration in unilaterally paralyzed larynx and vocal function. *Acta Otolaryngol* 2013;**133**:187–93.
26. Hara H, Hori T, Sugahara K, Yamashita H. Surgical planning of Isshiki type I thyroplasty using an open-source Digital Imaging and Communication in Medicine viewer OsiriX. *Acta Otolaryngol* 2014;**134**:620–5.
27. D'Andrilli A, Maurizi G, Andreetti C, Ciccone AM, Ibrahim M, Poggi C, et al. Long-term results of laryngotracheal resection for benign stenosis from a series of 109 consecutive patients. *Eur J Cardiothorac Surg* 2016;**50**:105–9.
28. Macchiarini P, Verhoye JP, Chapelier A, Fadel E, Dartevelle P. Partial cricoidectomy with primary thyrotracheal anastomosis for postintubation subglottic stenosis. *J Thorac Cardiovasc Surg* 2001;**121**:68–76.
29. Ashiku SK, Kuzucu A, Grillo HC, Wright CD, Wain JC, Lo B, et al. Idiopathic laryngotracheal stenosis: effective definitive treatment with laryngotracheal resection. *J Thorac Cardiovasc Surg* 2004;**127**:99–107.
30. Marulli G, Rizzardi G, Bortolotti L, Loy M, Breda C, Hamad AM, et al. Single-staged laryngotracheal resection and reconstruction for benign strictures in adults. *Interact Cardiovasc Thorac Surg* 2008;**7**:227–30.
31. Morshed K, Trojanowska A, Szymański M, Trojanowski P, Szymańska A, Smoleń A, et al. Evaluation of tracheal stenosis: comparison between computed tomography virtual tracheobronchoscopy with multiplanar reformatting, flexible tracheofiberoscopy and intra-operative findings. *Eur Arch Otorhinolaryngol* 2011;**268**:591–7.
32. Taha MS, Mostafa BE, Fahmy M, Ghaffar MK, Ghany EA. Spiral CT virtual bronchoscopy with multiplanar reformatting in the evaluation of post-intubation tracheal stenosis: comparison between endoscopic, radiological and surgical findings. *Eur Arch Otorhinolaryngol* 2009;**266**:863–6.
33. Hoppe H, Dinkel HP, Walder B, von Allmen G, Gugger M, Vock P. Grading airway stenosis down to the segmental level using virtual bronchoscopy. *Chest* 2004;**125**:704–11.
34. Crafts TD, Ellsperman SE, Wannemuehler TJ, Bellicchi TD, Shipchandler TZ, Mantravadi AV. Three-dimensional printing and its applications in otorhinolaryngology-head and neck surgery. *Otolaryngol Head Neck Surg* 2017;**156**:999–1010.
35. Balakrishnan K, Cofer S, Matsumoto JM, Dearani JA, Boesch RP. Three-dimensional printed models in multidisciplinary planning of complex tracheal reconstruction. *Laryngoscope* 2017;**127**:967–70.
36. Han B, Liu Y, Zhang X, Wang J. Three-dimensional printing as an aid to airway evaluation after tracheotomy in a patient with laryngeal carcinoma. *BMC Anesthesiol* 2016;**16**:6.
37. Tam MD, Laycock SD, Jayne D, Babar J, Noble B. 3-D printouts of the tracheobronchial tree generated from CT images as an aid to management in a case of tracheobronchial chondromalacia caused by relapsing polychondritis. *J Radiol Case Rep* 2013;**7**:34–43.
38. Chang JW, Park SA, Park JK, Choi JW, Kim YS, Shin YS, et al. Tissue-engineered tracheal reconstruction using three-dimensionally printed artificial tracheal graft: preliminary report. *Artif Organs* 2014;**38**:E95–E105.
39. Fiorelli A, Scaramuzzi R, Minerva I, De Ruberto E, Califano T, Reginelli A, et al. Three-dimensional (3D) printed model to plan the endoscopic treatment of upper airway stenosis. *J Bronchology Interv Pulmonol* 2018;**25**:349–54.
40. Arcieri L, Giordano R, Bellanti E, Chiappino D, Murzi B. Impact of 3D printing on the surgical management of tracheal stenosis associated to pulmonary sling: a case report. *J Thorac Dis* 2018;**10**:E130–3.
41. Legocki AT, Duffy-Peter A, Scott AR. Benefits and limitations of entry-level 3-Dimensional printing of maxillofacial skeletal models. *JAMA Otolaryngol Head Neck Surg* 2017;**143**:389–94.
42. Hsieh TY, Cervenka B, Dedhia R, Strong EB, Steele T. Assessment of a patient-specific, 3-dimensionally printed endoscopic sinus and skull base surgical model. *JAMA Otolaryngol Head Neck Surg* 2018;**144**:574–9.