European Archives of Oto-Rhino-Laryngology

Presentation of Complex Laryngotracheal Surgeries Using CT-based 3D Models and 3D Printing: A technical note.

--Manuscript Draft--

Manuscript Number:	EAOR-D-25-00527R2
Full Title:	Presentation of Complex Laryngotracheal Surgeries Using CT-based 3D Models and 3D Printing: A technical note.
Article Type:	Head & Neck (Original Article)
Keywords:	laryngotracheal surgery; 3D printing; virtual models; extended vertical hemilaryngectomy; glottic cancer; rotational crico-thyrotracheopexy; medical education
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Abstract:	Slide laryngotracheopexy for cricotracheal stenosis and extended partial laryngectomy combined with tracheopexy for T2-T3 glottic tumors represent novel, complex laryngotracheal surgeries requiring meticulous preoperative planning. In addition to conventional diagnostic tools (imaging, endoscopy), digital/virtual 3D techniques along with 3D printing - also referred to as Additive Manufactoring (AM)- allow for the creation and application of CT-based virtual and 3D-printed models of the larynx and the trachea. These 3D technologies can facilitate surgical team preparation and provide an innovative approach to training on complex surgical solutions. This paper presents the digital workflow for three cases where patient-specific 3D laryngotracheal models were developed and successfully applied in surgical planning and training. These models serve as high-fidelity anatomical representations for surgical rehearsal, training, and patient communication, demonstrating their potential for broader clinical implementation.

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European Archives of Oto-Rhino-Laryngology
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22.05.2025.

Dear Prof. Dr. med. Andreas Knopf,

I am submitting this revised version of my manuscript (ID: EAOR-D-25-00527R1), titled "Presentation of Complex Laryngotracheal Surgeries Using CT-based 3D Models and 3D Printing: A Technical Note."

As of this submission, I have not received any reviewer comments in the decision letter, even though the system indicates a "Revise" status. I have made no changes to the latest version of the manuscript because there were no comments on what revisions were expected.

If there is specific feedback or additional directions, I would be glad to revise the manuscript accordingly.

Thank you for your time and input.

Sincerely,
Dr. Tóbiás Zoltán

Presentation of Complex Laryngotracheal Surgeries Using CT-based 3D Models and 3D Printing: A technical note.

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ABSTRACT

Slide laryngotracheopexy for cricotracheal stenosis and extended partial laryngectomy combined with tracheopexy for T2-T3 glottic tumors represent novel, complex laryngotracheal surgeries requiring meticulous preoperative planning. In addition to conventional diagnostic tools (imaging, endoscopy), digital/virtual 3D techniques along with 3D printing - also referred to as Additive Manufactoring (AM)- allow for the creation and application of CT-based virtual and 3D-printed models of the larynx and the trachea. These 3D technologies can facilitate surgical team preparation and provide an innovative approach to training on complex surgical solutions. This paper presents the digital workflow for three cases where patient-specific 3D laryngotracheal models were developed and successfully applied in surgical planning and training. These models serve as high-fidelity anatomical representations for surgical rehearsal, training, and patient communication, demonstrating their potential for broader clinical implementation.

KEYWORDS: laryngotracheal surgery, 3D printing, virtual models, extended vertical hemilaryngectomy, glottic cancer, rotational crico-thyrotracheopexy, medical education

STATEMENTS AND DECLARATIONS

This work has not been previously published or submitted elsewhere. The corresponding author has read the author's guidelines.

Funding: No financial support was received for the research or writing of this article.
Conflict of interest: The authors have no conflict of interest to disclose.
Ethics approval: We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with this guideline. The ETT-TUKEB Hungarian National Ethical Committee granted ethical approval for this study, serial number BM/27869-3/2024.
Consent for publication: Each author listed on the manuscript has seen and approved the submission of this version of the manuscript and takes full responsibility for the manuscript.
Written informed consent was obtained from the participants.
Conflicts of Interest: The authors declare no conflicts of interest.
Acknowledgments: We thank the Institute of Surgical Research, Faculty of Medicine, University of Szeged, for providing equipment and educational facilities.

Presentation of Complex Laryngotracheal Surgeries Using CT-based 3D Models and 3D Printing: A technical note.

Introduction

Innovative open-neck surgical techniques for managing cricotracheal stenosis and T3-stage advanced glottic tumors of the larynx offer promising, organ-preserving solutions that avoid tracheostomy and support good respiratory, swallowing, and phonation function. Such procedures include slide laryngotracheopexy for high-grade cricoid and upper tracheal stenosis and extended partial laryngectomy combined with tracheopexy for T3 glottic tumors affecting the cricoid and thyroid cartilages. Both procedures use an elevated tracheal flap closure to address tissue deficits created by partial resection of the cricoid cartilage, which is fundamental to laryngeal stability. The surgical steps and postoperative results of extended partial laryngectomy with rotational tracheopexy and slide laryngotracheopexy have been previously published. [1-6]

Successful outcomes for these surgeries rely on creating a tension-free anastomosis, as both procedures reconfigure the laryngeal structure, requiring precise attention to the patient's individual anatomical conditions. Additionally, mastering these innovative techniques is challenging for clinicians, as these organ-preserving surgical solutions demand complex visualization and specialized training. Such complex surgeries are performed selectively, and careful surgical planning is crucial. Beyond conventional diagnostic tools (imaging and endoscopy), digital 3D techniques and 3D printing allow for the creation of CT-based virtual and 3D-printed "real" models of the larynx and the trachea.[7,8] These methods, leveraging the advantages of 3D technology, not only assist the surgical team in preparing for the intervention but also offer an innovative approach to teaching complex surgical techniques. Thanks to recent technical advancements, the equipment and software needed for such applications are now widely accessible. [9,10]

In this study, we present the workflow developed by our team, which enables preoperative planning and surgical technique training using both patient-specific virtual and 3D-printed laryngotracheal models. The process is demonstrated through a series of cases, where slide laryngotracheopexy was performed for idiopathic subglottic stenosis and an extended fronto-anterior partial laryngectomy for T3 glottic tumor involving the subglottis.

Materials and methods

The ethical approval for the study was granted by the ETT-TUKEB committee by the laws in force in Hungary. Approval number: BM/27869-3/2024.

Patient Material

This preliminary study included patients of any age and gender undergoing laryngotracheal surgery for advanced laryngeal cancer or cricotracheal stenosis. Patients with significant imaging artifacts, previous endolaryngeal or open-neck laryngotracheal surgery, or tracheotomy were excluded to ensure segmentation accuracy.

Methodology for Creating Realistic 3D Models

Segmentation Based on High-Resolution Computed Tomography (HRCT)

We used pre- and postoperative HRCT scans in DICOM format, processed using ITK-SNAP software (ITK-SNAP, 2009, http://www.itksnap.org). Manual segmentation was performed by comparing the CT scans in three planes, with input from a radiologist skilled in head and neck anatomy, to ensure an accurate assessment of the anatomical structures and pathological changes. Different regions were labeled for segmentation as follows: 1. Hyoid bone; 2. Thyroid cartilage; 3. Cricoid cartilage; 4. Trachea; 5. Glottis; 6. Epiglottis; 7. Aryepiglottic fold; 8. Arytenoids; 9. Tumor/stenosis. We referred to preoperative laryngoscopic images to evaluate lesion details accurately. Segmentation was conducted on a MacBook Pro M1 (Apple, 2022, Cupertino, CA, USA), paired with a Wacom Cintiq 24 HD display and a digital pen (Wacom, 2021, Kazo, Saitama, Japan). Segmentation is shown in Figure 1.

Refinement Using 3D Digital Sculpting Techniques

After completing the segmentation, we exported the “mesh” model (a term used in 3D graphics to describe the surface network of a model) as an STL file. This file was then refined using digital sculpting techniques in the Nomad Sculpt software (Hexanomad, Nomad Sculpt (Version: 1.97, Stéphane Ginier, Paris, France, 2024, https://nomadsculpt.com).

We smoothed and adjusted the mesh surface during refinement, making minimal additions to ensure surface uniformity. We used anatomical atlases to make slight adjustments to the digital 3D data where CT resolution limitations restricted the visibility of specific anatomical details (e.g., the subtle contours of the hyoid bone’s anterior surface or the fibers of the thyrohyoid membrane). Critical areas, such as malignant tumors or stenoses, were highlighted with distinct colors for easier identification. This process was conducted on an Apple iPad Pro 12.9” tablet with an Apple Pencil (Apple, 2022, Cupertino, CA, USA). The process is shown in Figure 2.

3D Printing and Model Utilization

This study utilized two different 3D printing technologies: Material Extrusion (MEX) and VAT photopolymerization (VPP). The MEX technique was performed using a Voxelab Aquila 3D printer (Voxelab, 2021, Jinhua, Zhejiang Province, China) with thermoplastic polyurethane (TPU) as the printing material. Preparation for 3D printing was carried out using VoxelMaker software (v. 1.2.8., Voxelab, Jinhua, Zhejiang Province, China). The VPP printing process was carried out on a Form3 printer (Formlabs Inc.) using Formlabs Flexible 80A resin. Print preparation was conducted using specialized software, including Preform (Formlabs Inc.) and 3D Sprint (3D Systems Inc.).

Results

We applied our CT-based 3D modeling and printing workflow to three cases, progressively refining our methodology. For detailed patient info, see Tablet 1. The first case focused on virtual modeling, proving useful for education and surgical planning. In the second case, we successfully printed our first physical model, testing materials and evaluating feasibility. In the third case, we implemented an improved VPP printing process, producing a detailed, flexible, and surgically applicable model. The final model was validated in a simulated surgical setup, demonstrating its potential for preoperative planning and hands-on training.

In *Case 1*, a patient with advanced T3 glottic carcinoma underwent an extended partial laryngectomy with rotational tracheopexy. We used preoperative and postoperative HRCT images for segmentation to interpret the anatomical changes and to communicate the overall concept of the surgery. After digital post-processing, the virtual model was visualized and used for graduate medical education (5th-year students), professional surgical training, and a presentation at the National Otolaryngology Congress. Models are shown in Figure 3.

Based on the success of the virtual model, we proceeded with our first physical 3D printing attempt with *Case 2*. A patient with idiopathic subglottic stenosis underwent slide laryngotracheopexy. After segmentation and post-processing, the virtual model was refined for 3D printing (see Figure 4). The goal was to evaluate the printing workflow, material feasibility, and anatomical accuracy. The model was printed in real size using the MEX printing method with thermoplastic polyurethane (TPU), chosen for its availability and flexibility. The printing process was successful, producing an anatomically recognizable model, but several limitations emerged. The print resolution was relatively low (XY: 100 μm / Z:300 μm with TPU filament diameter 1,75mm), affecting fine anatomical details. Additionally, while TPU provided some flexibility, it lacked the necessary softness and realism required for fine surgical manipulation. Despite these limitations, the

MEX attempt was a valuable proof-of-concept, demonstrating that the 3D printing of the laryngotracheal complex was achievable. To better understand what changes are necessary and what the surgical experience is like, we performed the slide laryngotracheopexy procedure on the first model. The printed model was placed inside a head-neck mannequin, designed for educational purposes, with a slot at the laryngeal area. Once secured, the model was covered with a silicone sheet that simulated skin, allowing for the simulation of incisions, surgical exposure, and planned procedural steps. While the resection was challenging due to the material's hardness, the suturing experience was surprisingly positive. The material did not tear, enabling the suturing technique to be executed accurately under surgical conditions. We recognized during the process that a softer, more delicate material would be necessary. The setup with the model and the surgical process is shown in Figure 5.

To overcome the limitations identified in *Case 2*, we collaborated with 3D printing professionals and transitioned to VPP printing technology using the Formlabs Flexible 80A resin. This printing technology, in general, and the selected material, in particular, was chosen for its high resolution and favorable biomechanical properties, making it suitable for suturing and resection simulations. The printing resolution was 100 µm for the Z-axis (layer height) and 25 µm for the XY-axis.

We have also prepared the virtual preoperative model for *Case 3*, representing an advanced T3 glottic carcinoma with cricoid invasion (see Figure 6). The final resin model exhibited remarkable anatomical detail, accurately representing even the cartilaginous and soft tissue structures. Additionally, the resin’s flexibility (nominally exhibiting 80 Shore A hardness) enabled realistic surgical manipulation, allowing for suture placement, incisions, and resections similar to intraoperative conditions.

The model was validated in the same pre-prepared mannequin setup, where it was subjected to simulated surgical procedures. The surgeons reported that the VPP-printed model provided a realistic, hands-on experience, confirming its potential as a preoperative planning tool and an advanced educational model. Compared to the previous case, this iteration was significantly superior, demonstrating the importance of iterative refinement in medical 3D printing. The model and the setup are shown in Figure 7. We even compared the images taken during the key steps of the surgery (determining the resection margins and creating the anastomosis) with the intraoperative photos to evaluate similarities (Figure 8).

Discussion

Complex, reconstructive laryngotracheal surgeries are often performed after previous unsuccessful interventions or to avoid the poor quality of life outcomes associated with conventional techniques. Although imaging and endoscopic diagnostics are essential for surgical planning, the increasing availability of high-performance digital tools makes it possible to incorporate 3D techniques into surgical preparation.

In fields like implantology and complex bone reconstruction, 3D surgical planning has long been standard practice. In tracheal and cardiac surgery, 3D printing is already employed for surgical simulation and trial procedures.[18] Additionally, there is literature on using 3D-printed models for interventions in both adult and pediatric vocal cord paralysis. [6]

Randomized clinical studies across various surgical specialties have demonstrated the effectiveness of patient-specific 3D-printed models beyond the field of otorhinolaryngology. For example, developing detailed 3D models of the lung and target lesions in thoracic surgery has enabled precise preoperative simulation. This approach has significantly reduced operative time, intraoperative blood loss, and conversion rates during video-assisted thoracoscopic segmentectomy (VATS) for wedge resection of ground-glass nodules [25]. Similarly, the use of 3D-printed models for preoperative planning in middle-upper thoracic trauma has led to a notable decrease in surgical errors and operative time during pedicle screw placement [26]. In pediatric liver transplantation, 3D-printed models have also been shown to reduce the risk of postoperative complications and enhance surgical safety, underscoring their value in high-risk, anatomically complex procedures [27]. These findings provide strong support for the clinical potential of 3D-printed models in improving surgical outcomes, and they further justify our intention to conduct a randomized clinical study to evaluate their efficacy in complex laryngotracheal surgeries.

While 3D preoperative planning is becoming more common in otolaryngology and head and neck surgery, especially for procedures in the temporomandibular region and ear surgery, preoperative 3D planning for complex laryngeal resections remains underutilized. [12-14] This is likely due to the complex anatomy of the pharyngeal-laryngeal area and the narrow density spectrum of adjacent tissues on imaging, which can complicate segmentation in pathological cases. Thus, continuous collaboration among otolaryngologists, radiologists, and the surgical team with expertise in head and neck surgery is essential for developing these methods.

Machine learning-based methods are gaining traction, as well-trained artificial intelligence (AI) models may produce convincing results in making 3D models from imaging data. Future developments will integrate AI-based segmentation techniques to automate model generation, reducing manual processing time and inter-operator variability. [15] Recent advancements in deep learning segmentation have demonstrated promising results in airway modeling, which we aim to incorporate into future iterations of our workflow. [16]

Traditional silicone models, long an integral part of medical training, allow for practicing various procedures and endoscopic and instrumental exercises. Although these models realistically represent anatomical relationships, they are not replicas of individual organs or regions. Studies comparing traditional silicone models with 3D-printed anatomical replicas highlight the superior realism and customization of 3D-printed models, making them highly effective for training in complex surgical techniques. [17] [19] In dental education, 3D-printed replicas of real teeth are available for technique practice, and this approach has proven effective in the literature. Our goal was to create models that closely replicate the geometry of the patient's larynx, allowing the surgeon to handle and study the model before any intervention takes place. To promote the widespread adoption of innovative surgical techniques, 3D models of previously operated cases, both in virtual and printed form, can provide valuable information in training sessions and courses and integrate into current graduate education programs.

It is advisable to identify anatomical structures during segmentation by comparing multiple planes, particularly for the vocal cords and supraglottic structures, which can be challenging. It is essential to correlate endoscopic images with CT findings to accurately evaluate endolaryngeal abnormalities. The ITK-SNAP software allows real-time monitoring of the initial 3D model's development during segmentation, enabling verification of the model's accuracy throughout the process. [11,12]

Post-processing was essential to enhance surface uniformity, correct segmentation artifacts, and improve printability. Digital sculpting techniques were used during this phase. This step ensured that fine anatomical structures (e.g., cricoid cartilage contours and subglottic stenosis margins) were preserved and further increased the realism of the model. Digital pens and capacitive displays have notable advantages over traditional monitors and mouse usage. The pen is significantly easier and faster to use than a mouse, allows for finer manual control, and a digitizing tablet is a cost-effective alternative to capacitive display with a similar functionality. It is worth noting that the hardware setup we used was high-performance, designed for processes even more hardware-intensive than segmentation; thus, a lower-performance system would suffice for this segmentation process.[13]

For 3D printing, we selected a material that offers some degree of physical manipulability. We opted for resin Flexible 80A, due to its suitability to maintain geometric form while being shapeable to a certain extent with surgical instruments and sutures. We considered the cost of available printers and materials throughout this research. [22] The printed models effectively demonstrated the main steps of slide laryngotracheopexy and extended fronto-anterior partial laryngectomy. Additionally, the models can be manipulated in real-time in a virtual environment, providing a vivid demonstration of the surgical steps. During the model surgery, we were also able to simulate the positioning of the endotracheal tube, as the model was suitable for inserting the same type of tube used in our procedures. One of the key steps in complex laryngotracheal surgeries is reintubation through the tracheostomy opening. During the anastomosis suturing, frequent mobilization of the tube is often required, and practicing this process can significantly enhance the safety of the actual surgical procedure.

Our results demonstrate that transitioning from virtual modeling to 3D-printed surgical models requires careful material selection. While MEX printing was an effective feasibility test, it lacked the necessary flexibility and detail for true surgical rehearsal. Case 2 highlighted the need for a higher-resolution printing method and better material selection. Based on this experience, we sought professional input from 3D printing specialists and decided to upgrade to VPP printing. In the next case, VPP printing, by contrast, produced highly detailed, suturable, and resectable models, validating its use in preoperative planning. [23,24] This aligns with previous studies in tracheal and cardiac surgery, where VPP models have been shown to enhance surgical preparation. Future work will focus on scaling up patient studies, refining materials further, and integrating AI-assisted segmentation for automation.

The novel, non-conventional surgical interventions we applied are often performed after previous unsuccessful surgeries or treatments, resulting in a strong need for precise patient information about expected outcomes. Visual aids, such as drawings or videos, can be extremely helpful for patient education beyond general explanations. It is particularly meaningful for patients to examine their affected organs in virtual or printed form and compare pre- and postoperative conditions, providing a clearer understanding of the changes they have undergone. This principle extends beyond laryngology to several other surgical disciplines. Patient-specific 3D models have been shown to enhance patient–physician communication and medical education by providing tangible, anatomically accurate representations of pathology. Studies have demonstrated positive outcomes when patients received education using 3D-printed models of their own anatomy, for example, in cases of pediatric congenital heart defects and craniofacial malformations or trauma, resulting in improved understanding, engagement, and satisfaction.[28,29] This process greatly enhances doctor-patient communication, benefiting both parties. Therefore, we also plan to involve our models in patient education, in general.

Limitation

Despite the promising findings, this study has limitations. The sample size at present is limited to three cases, requiring further subjective and objective validation in a larger sample size. We aim to expand the study to a larger cohort (n≥20 patients) for further validation. Segmentation remains a challenge due to its time-consuming nature, but future studies could benefit from AI-driven automation to streamline the process.

Conclusions

CT-based 3D laryngotracheal models refined with digital methods offer an innovative, high-fidelity approach to surgical planning, visualization, and training. These models have demonstrated effectiveness in both virtual and printed forms, providing anatomically accurate, patient-specific insights. Future work will focus on multi-institutional validation, AI-assisted segmentation, and material advancements to enhance model precision and expand clinical implementation in airway surgery.

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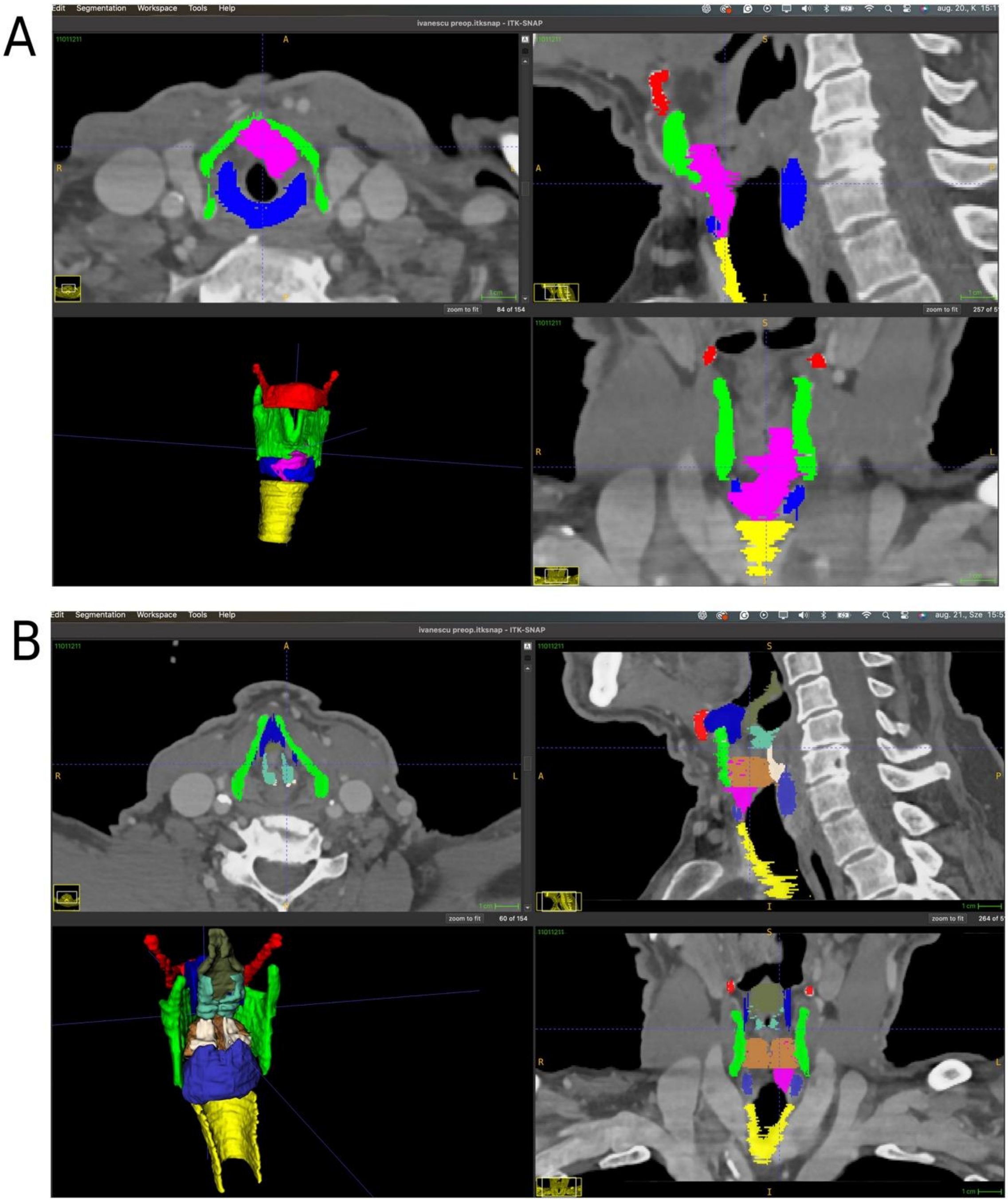
Figure 1



1. Figure. Screenshots of ITK Snap software during the manual segmentation process are shown in *Case 3.*
Color legend: red – hyoid bone; green – thyroid cartilage; blue – cricoid cartilage; violet – tumor; light blue – epiglottis; brown – glottis; white – arytenoids; yellow – trachea.
A – A generated 3D model(low-left picture) is made by ITK Snap software based on the segmentation. The model is shown from of view with the corresponding CT images
B – posterior view (low-left picture) of the model is shown during the segmentation of with the corresponding CT images od Case 3.

Figure 2

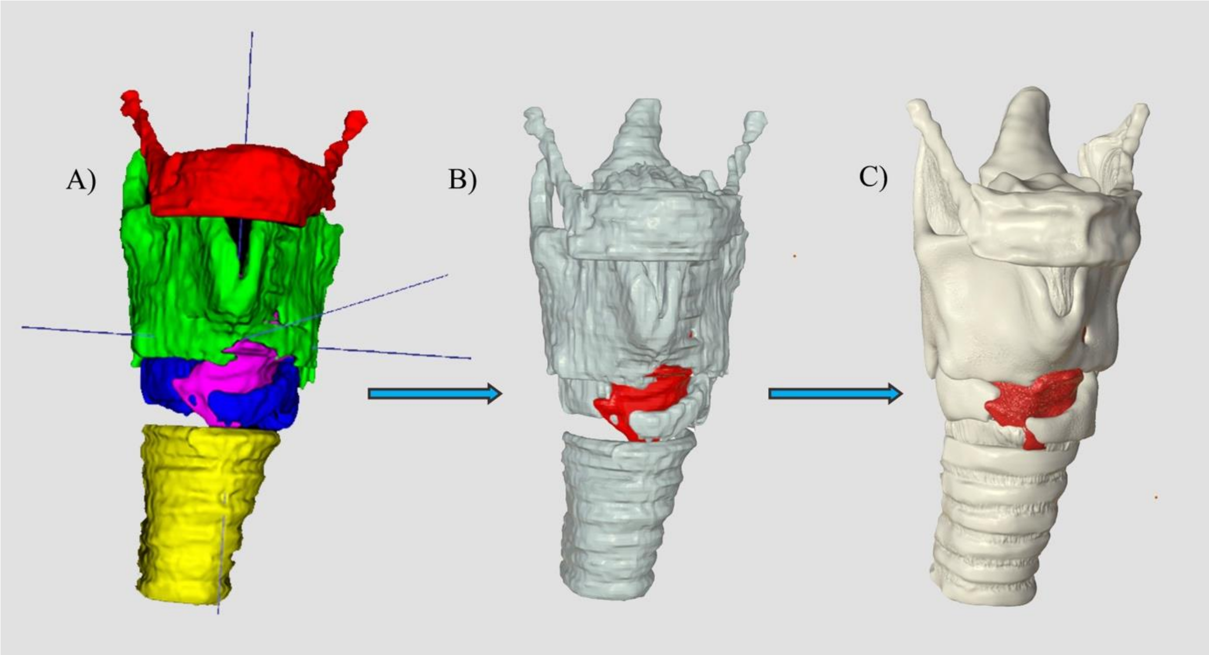


Figure 2. The process of the virtual model creation is shown.

A - 3D model generated by ITK Snap software based on the manual segmentation. Color legend: red – hyoid bone; green – thyroid cartilage; violet – tumor; blue – cricoid cartilage; yellow – trachea.
B - The generated 3D model is opened in Nomad Sculpt. Tumor extension is highlighted with red color.
C – The final virtual model after post-processing is shown. Tumor extension is highlighted in red color.

Figure 3

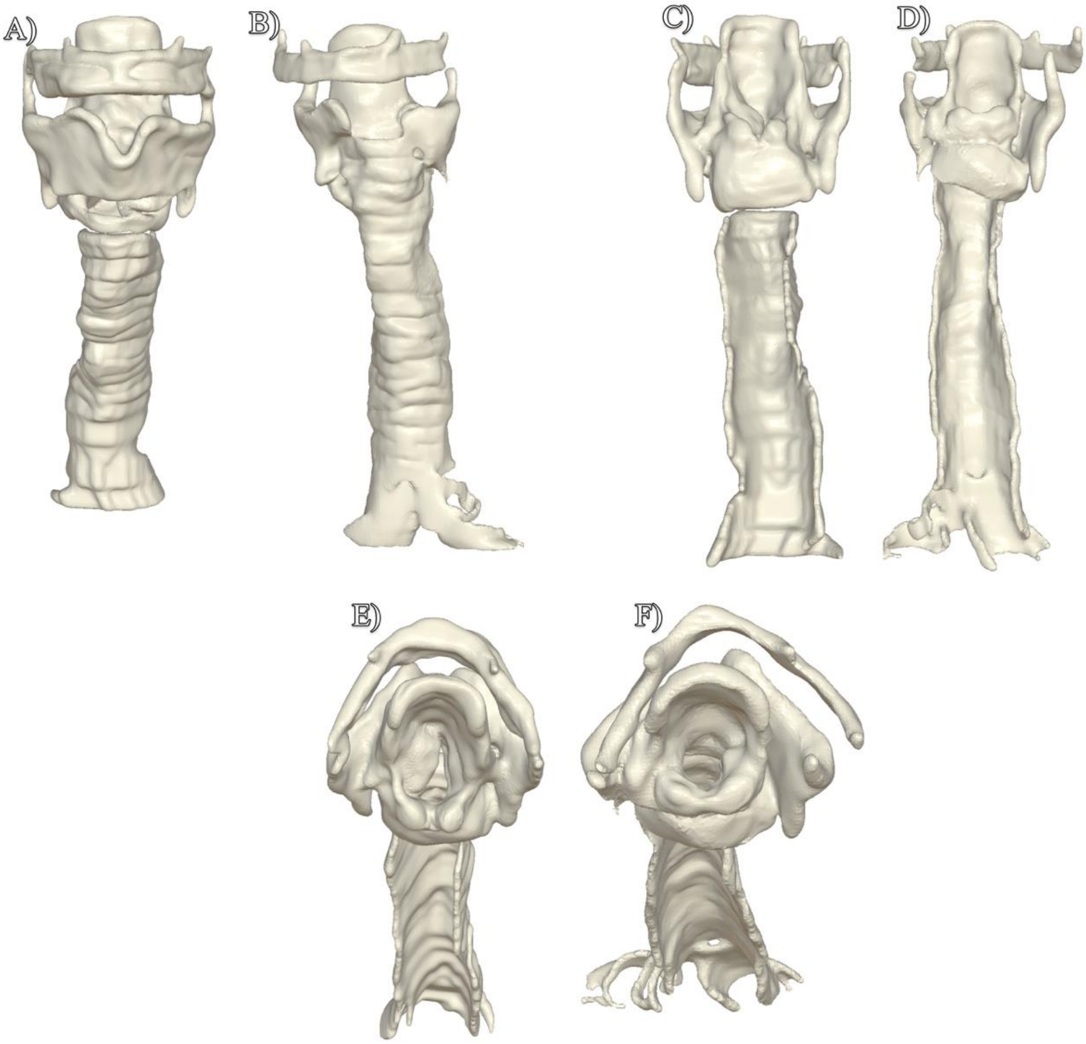


Figure 3. Virtual interpretation of pre-and postoperative laryngotracheal anatomy after extended hemilaryngectomy with rotational thyro-tracheopexy in *Case 1*.

A, B – Pre- and postoperative model from frontal view after digital post-processing.
C, D – Pre-and postoperative model from back view after digital post-processing.
E, F – Pre- and postoperative model from superior view after digital post-processing.

Figure 8

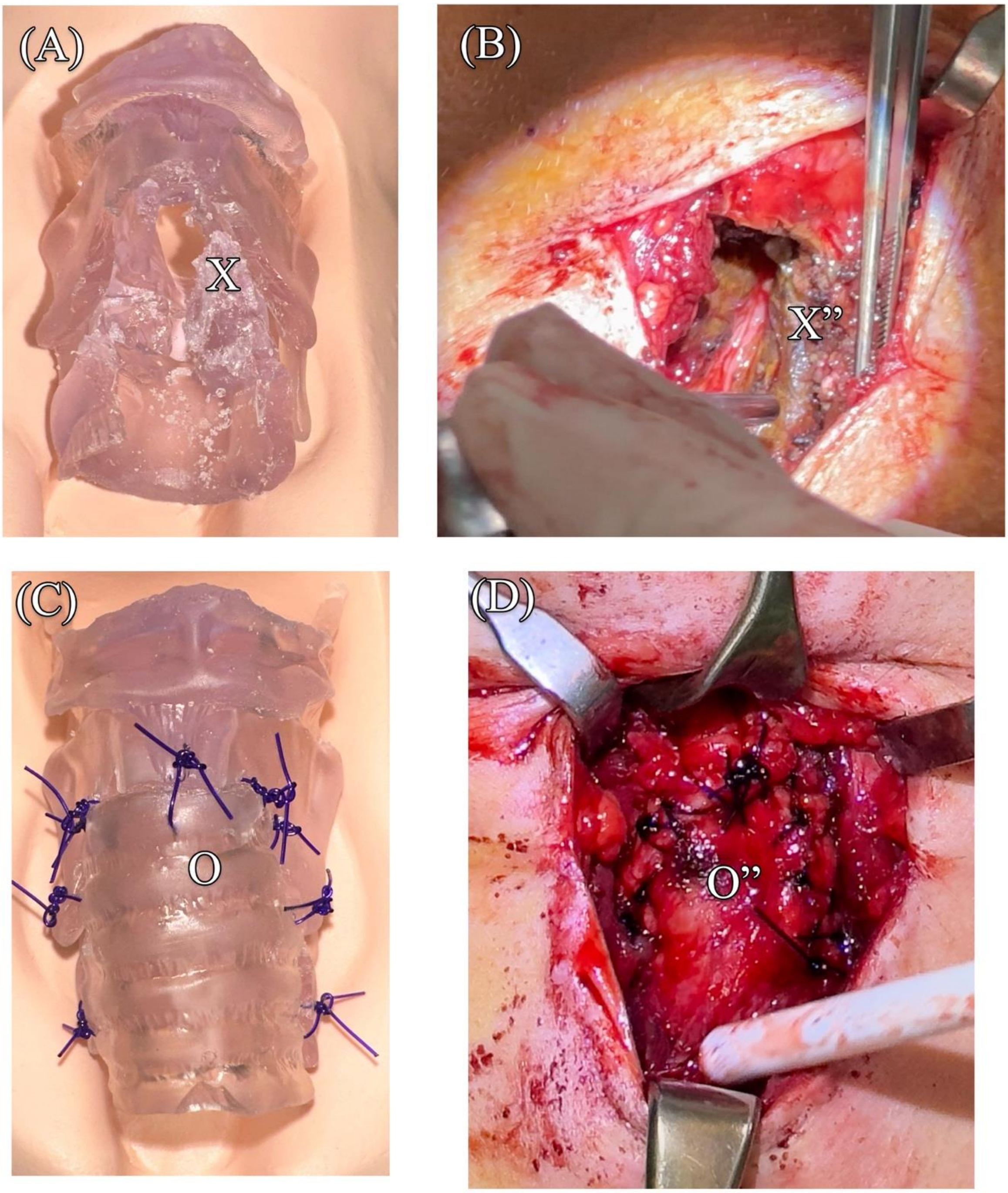


Figure 8. The comparison of the laryngotracheal model and the intraoperative surgical status of Case 3.

A – VPP printed laryngotracheal model from the frontal view.
B – Intraoperative photo of Case 3 during the resection of the tumor
X and X'' represent identical parts of the thyroid lamina with tumor invasion.
C – VPP printed laryngotracheal model with complete anastomosis
D – Intraoperative photo of Case 3 after completing the anastomosis.
O and O'' represent identical parts of the anterior wall of the trachea.

Figure 4

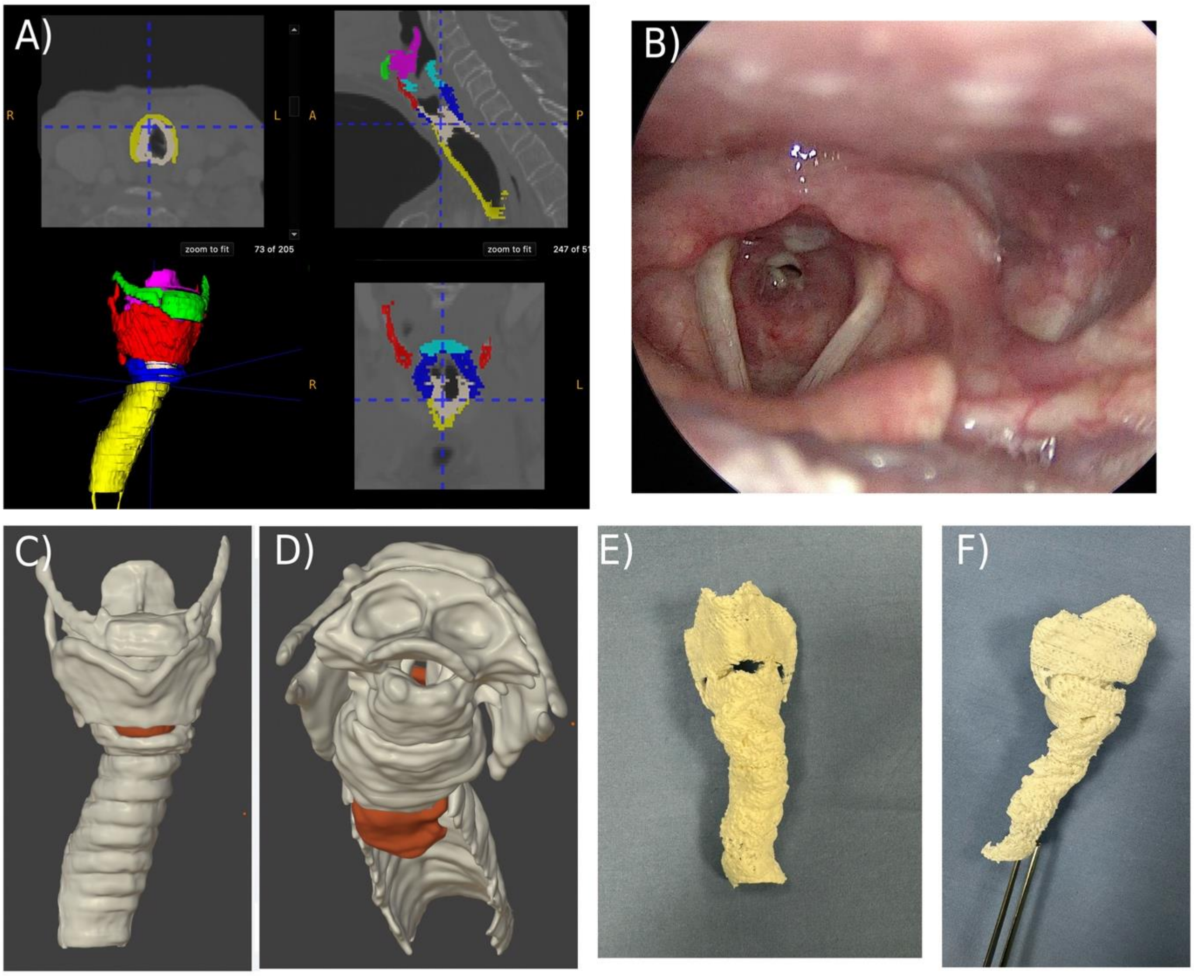


Figure 4. Steps and materials used during the creation of the preoperative 3D model in *Case 2*.

A – The preoperative CT image and the segmentation process are shown. Color legend: green – hyoid bone; red – thyroid cartilage; dark blue – cricoid cartilage; light blue – glottis; violet – epiglottis; yellow – trachea; grey – stenosis.
B – A preoperative endoscopic image of the Cotton-Myers III grade subglottic stenosis.
C, D – Refined virtual model after segmentation, frontal and superior view. Stenosis is indicated with the orange color.
E, F – MEX printed models of *Case 2*, frontal and side views.

Figure 5

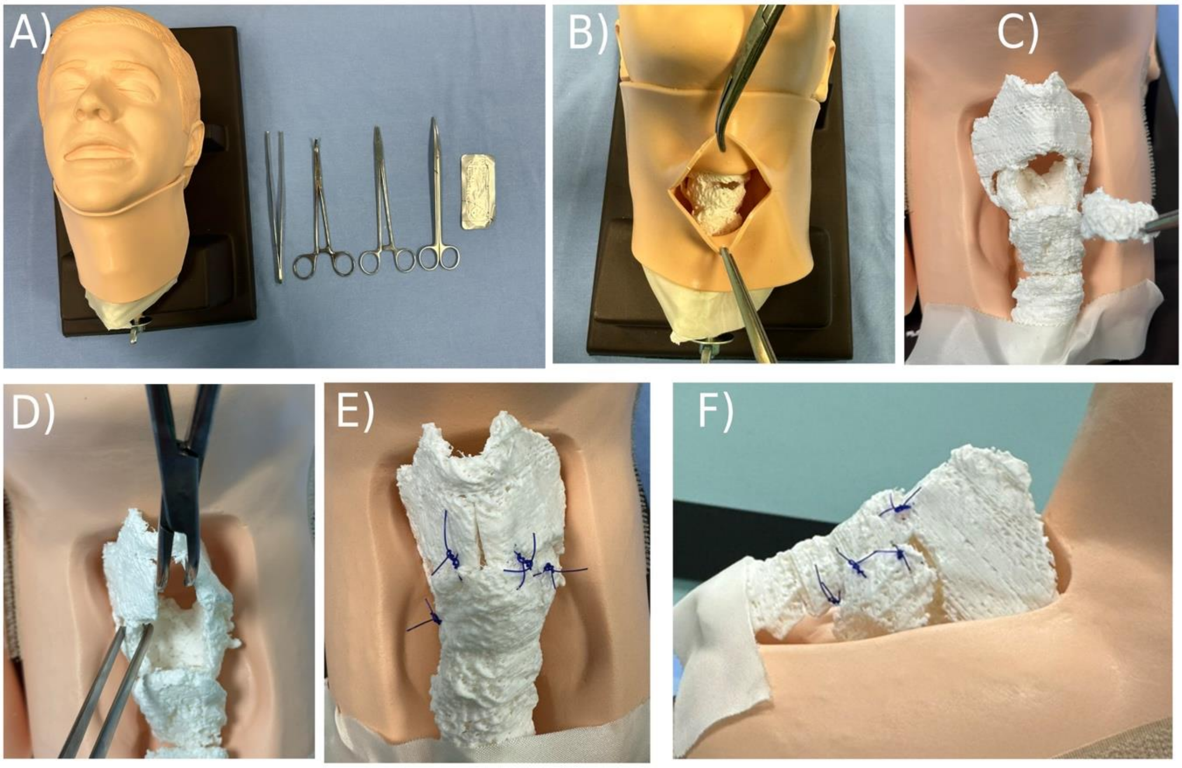


Figure 5. The preoperative 3D model of Case 2 was printed with MEX printing technique using TPU filament.

A – The head-neck mannequin is shown with the surgical instruments. The printed model is placed in the socket of the neck part and covered with a silicone sheet.
B – The silicon sheet is incised according to the first step of slide laryngotracheopexy.
C – The subglottic space is widened as the stenotic part has been removed, and the cricoid arch is expanded.
D – After laryngofission, the subglottic space is further widened by the expansion of the laminas with forceps.
E – Sutures of the anastomosis are placed.
F – Side view of the laryngeal model after the surgery.

Figure 6

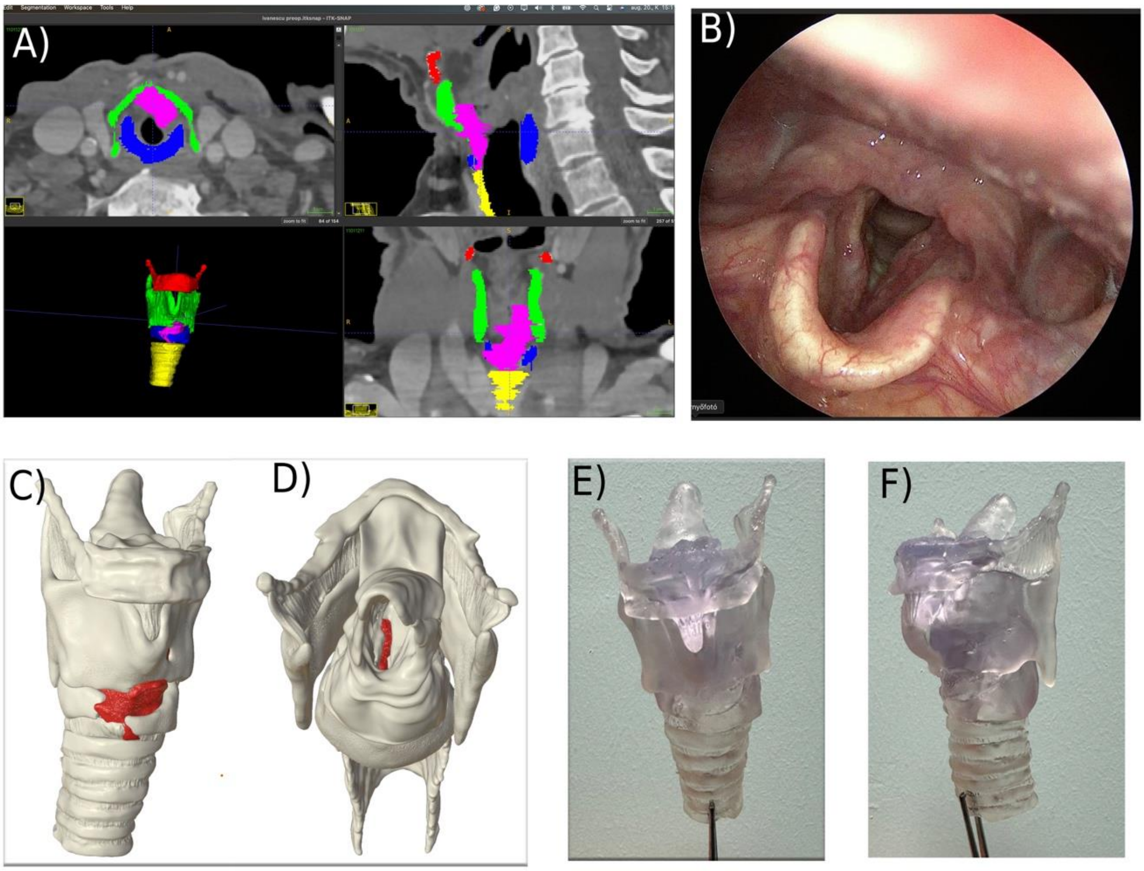


Figure 6. The creation of the preoperative laryngotracheal 3D model is shown in Case 3.

A – The manual segmentation is shown with the corresponding CT images. Color legend: red – hyoid bone; green – thyroid cartilage; violet – tumor; blue – cricoid cartilage; yellow – trachea.
B – Preoperative endoscopic image of patient#3.

C, D – 3D virtual model after post-processing shown from frontal and superior views.
E,F – VPP printed model based of *Case 3,* shown from frontal and lateral views.

Figure 7

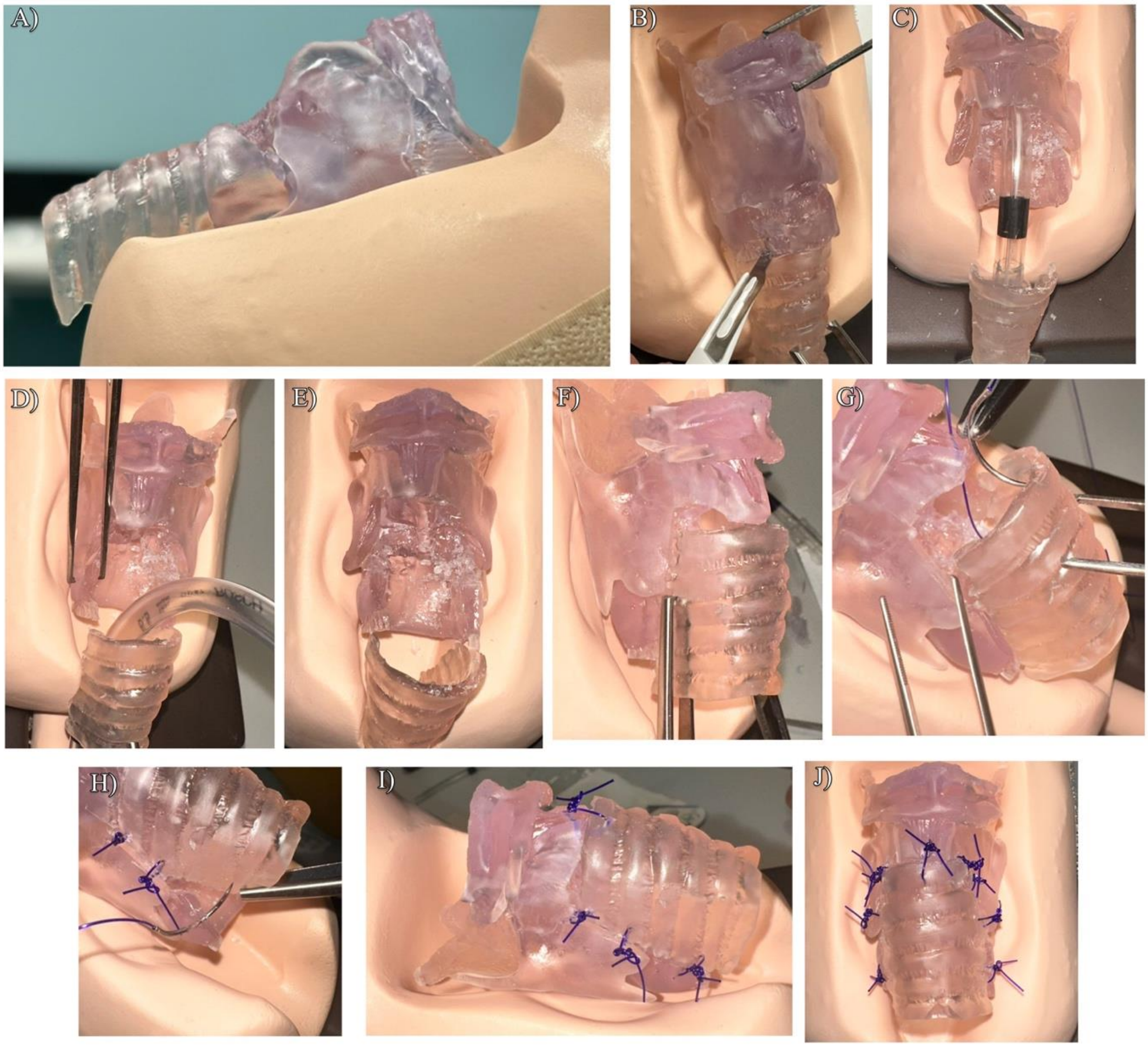


Figure 7. VPP printed model of *Case 3* is shown with the simulated surgical steps of extended hemilaryngectomy with tracheopexy.

A – The laryngotracheal model is placed in the socket of the training mannequin.
B – Incision is done on the cricoid arch.
C – Tube placement is simulated after the dissection of the cricotracheal junction
D – Reintubation in the trachea is simulated
E – Status after complete resection
F,G,H – Tracheopexy and anastomosis suturing are simulated
I,J – complete anastomosis is shown from the side and frontal views.

Table 1

Case	Patient	age[years]	sex	Condition	Surgical intervention
1	#1	62	male	left side T3 vocal chord squamous cell carcinoma with subglottic invasion	extended partial laryngectomy with rotational crico-thracheopexy
2	#2	64	female	Idiopathic subglottic stenosis, Cotton-Myers gr. III.	slide laryngotracheopexy
3	#3	75	male	right side T3 vocal chord squamous cell carcinoma with subglottic invasion	extended partial laryngectomy with rotational crico-thracheopexy