Innovative Approaches in Laryngotracheal Surgery and Medical Education

Surgical Techniques, 3D Modeling, and Educational Applications in Head and Neck Surgery

PhD Thesis

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II. Rovó L, Szakács L, Castellanos PF, et al. Extended partial laryngectomy with functional preservation using the rotational crico-tracheopexy. Laryngoscope Investig Otolaryngol. 2023;8:1328-1336.

III. Tóbiás, Z., et al. Presentation of Complex Laryngotracheal Surgeries Using CT-based 3D Models and 3D Printing: A Technical Note. Eur Arch Otorhinolaryngol. 2025. (Accepted, DOI pending)

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2. Bach Á, Ambrus A, Iványi B, Tóbiás Z, Alim Marvasti GH, Rovó L. IgG4-Related Laryngeal Disease as a Possible Cause of Idiopathic Subglottic Stenosis: A Case Report. *Iran J Otorhinolaryngol*. 2021;33(115):119-125. doi:10.22038/ijorl.2020.47106.2547

3. Tóbiás Z, Pálinkó D, Sztanó B, Csanády M, Gál P, Rovó L. A laryngomalacia endoszkópos ultrapulzációs-lézeres (ultra dream pulse) sebészete. A módszer hazai bevezetése során szerzett tapasztalataink [Endoscopic ultra dream pulse laser surgery of laryngomalacia. Our experiences gained during the introduction of the method in Hungary]. *Orv Hetil*. 2017;158(33):1288-1292. doi:10.1556/650.2017.30722

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1.Introduction

1.1 Clinical significance of cricotracheal stenosis and advanced glottic tumors

Laryngeal and tracheal pathologies, such as cricotracheal stenosis and advanced-stage laryngeal malignancies, present a significant challenge in head and neck surgery. Both conditions can cause progressive airway obstruction, significantly impairing respiration, phonation, and swallowing. If left untreated, they can result in severe dyspnea, stridor, and the need for urgent airway intervention; without therapy, laryngeal tumors lead to fatal complications. These conditions often require urgent, life-saving interventions, while careful consideration of the therapeutic approach is essential for long-term recovery and social reintegration.[1-5]

Idiopathic subglottic stenosis (iSGS) is a rare, progressive fibroinflammatory airway disorder with an unknown etiology. [6] Several conditions are known to cause cricotracheal stenosis with a similar presentation, including IgG4-related disease, GPA, and sarcoidosis. Stenosis of iatrogenic origin is typically observed following prolonged intubation or radiotherapy. In contrast, iSGS lacks an identifiable autoimmune background or distinct histopathological abnormalities. This condition is often misdiagnosed as asthma or COPD, leading to delays in appropriate intervention. [7,8] No conservative therapy can halt scar tissue formation. Without proper surgical management, patients may suffer from recurrent airway obstruction, often requiring multiple interventions and, in severe cases, a tracheostomy to maintain airflow. The absence of a standardized treatment protocol, combined with a high restenosis rate, presents significant challenges in long-term management. [10-12]

Laryngeal malignancies account for 2-5% of all cancers worldwide, with squamous cell carcinoma (SCC) being the predominant histological type. [13,14] While early-stage T1-T2 glottic tumors can be effectively treated with transoral laser surgery or radiotherapy, advanced-stage laryngeal tumors, particularly T3-stage malignancies, present unique surgical and oncological challenges. These tumors frequently invade critical laryngeal structures such as the cricoid cartilage, thyroid cartilage, anterior and posterior commissure, and cricoarytenoid joint, making function-preserving surgery more complex and, in some cases, unfeasible. [15,16] Total laryngectomy—the traditional standard for advanced cases ensures oncological control but at the cost of irreversible functional impairment. Patients undergoing total laryngectomy experience a permanent loss of phonation and require a tracheostomy, which significantly affects social interaction, psychological well-being, and respiratory function.[17]As a result, function-preserving surgical techniques have become a significant focus of modern laryngeal cancer management. [15]

Given the drawbacks of radical, mutilating surgeries, there is a growing focus on organ-preserving surgical interventions that ensure effective oncological ablation while achieving functionally acceptable results. Advances in minimally invasive airway reconstruction, laryngotracheal reconstruction, and function-preserving surgical methods can potentially enhance patient outcomes, decrease the need for repeat surgeries, and improve postoperative quality of life.

Additionally, utilizing three-dimensional (3D) techniques in surgical planning and modeling introduces a new aspect to head and neck surgery, allowing for personalized treatment strategies and better training opportunities for complex airway reconstructions. As these conditions present significant clinical and surgical challenges, further research into long-term surgical outcomes, recurrence prevention, and optimized airway reconstruction techniques is crucial for advancing treatment paradigms and overall patient prognosis.[18,19]

1.2 Pathophysiology and treatment strategies for idiopathic subglottic stenosis (iSGS)

Idiopathic subglottic stenosis is a rare, non-inflammatory airway disorder characterized by progressive stenosis of the subglottic region, resulting in increased respiratory distress, dyspnea, and stridor.[6] This condition disproportionately affects middle-aged women and is poorly understood. Unlike post-intubation or autoimmune-related tracheal stenoses, idiopathic subglottic stenosis occurs without a known inciting factor. The diagnosis is often delayed due to symptom overlap with asthma and chronic obstructive pulmonary disease, which can lead to misdiagnosis and mismanagement. [7,8]

Currently, no conservative therapy effectively halts or reverses subglottic scar progression, necessitating surgical management in nearly all cases. Endoscopic procedures are the first-line treatment in mild to moderate stenosis (Cotton-Myer I–II). Techniques such as balloon dilation, CO_2 laser excision, corticosteroid injections, and mitomycin-C applications have been employed in combination or monotherapy. While these interventions provide immediate symptomatic relief, their effects are often short-lived, as the underlying inflammatory process remains unresolved. Restenosis is common, and many patients require repeated procedures within months of their initial treatment. However, laser interventions progressively impair tissue regeneration due to collateral thermal damage, leading to a gradual decline in mucociliary clearance and tissue elasticity with each procedure.[10,20,21]

Open surgical interventions are necessary for high-grade (Cotton-Myer III-IV) or recurrent stenoses to achieve long-term airway stability. Cricotracheal resection (CTR) is the preferred approach for extensive stenotic lesions involving the partial or complete removal of the affected tracheal segment followed by end-to-end anastomosis. While CTR offers a high success rate in restoring airway function, it is associated with significant surgical risks, including anastomotic dehiscence, wound infection, and postoperative airway edema, which can lead to life-threatening complications. Additionally, CTR can affect the mobility of the cricoarytenoidal joint, leading to voice changes or dysphagia, which further impacts patients ' quality of life. The recurrence of iSGS poses another major challenge in long-term management. Many patients who undergo endoscopic or open surgical procedures eventually experience restenosis, requiring additional interventions within a relatively short period. Given the high recurrence rate, an ideal surgical approach should provide adequate airway patency, minimize the risk of restenosis, reduce the need for tracheostomy, and preserve essential laryngeal functions such as voice and swallowing. [22-24]

Given the limitations of conventional treatments, there has been a growing emphasis on developing new, function-preserving surgical approaches that offer better long-term outcomes with fewer complications. One such innovation is slide laryngotracheopexy, a novel technique that redefines the glottic and subglottic airway using a localized tracheal graft. Unlike traditional CTR, which involves the partial resection of the cricoid cartilage, slide laryngotracheopexy modifies the subglottic structure while preserving its overall integrity, reducing the likelihood of restenosis and eliminating the need for prolonged T-tube or tracheostomy placement. This surgical technique has been successfully incorporated in pediatric airway surgery in cases of congenital subglottic stenosis.[25-28]

1.3 Treatment of advanced-stage glottic tumors

The cricoid cartilage acts as the structural foundation of the larynx. Thus, when tumor invasion reaches the cricoid in cases of advanced glottic cancers, the surgical approach must be considered carefully, taking into account its potential effects on swallowing and respiratory function. [29] Locally advanced anterior commissure laryngeal carcinomas also pose a therapeutic challenge. While early-stage anterior commissure cancers can be effectively treated with transoral laser surgery or radiotherapy, either as a stand-alone treatment or as part of a multimodal approach, tumors invading the thyroid cartilage necessitate open-neck surgery.[30-35]

Historically, total laryngectomy has been viewed as the gold standard for managing advanced glottic tumors, especially in the elder patient population, where partial laryngectomy has a lower functional success rate. While this method ensures complete oncological control, it also results in the permanent loss of phonation and necessitates a lifelong tracheostomy, both of which lead to a significant decline in quality of life. [36]Even with modern speech rehabilitation interventions and assistive devices, such as esophageal implants or laryngeal microphones, the quality of natural communication remains severely impaired, contributing to social isolation and emotional distress. [37-39] Recognizing these challenges, laryngeal oncology has increasingly shifted focus toward organ-preserving surgical strategies that eradicate tumors while maintaining essential laryngeal functions, including voice and airway protection.

Over time, various function-preserving surgical approaches have developed to avoid the necessity of total laryngectomy while delivering effective oncological outcomes. Supraglottic and supracricoid laryngectomies have proven effective in managing early-stage tumors, but their use is often limited when addressing more extensive or infiltrative malignancies. [40] The classical partial laryngeal resection procedures (Leroux-Robert and modified Hautant) and extended interventions (Gluck-Soerensen and Pearson) were designed to avoid total laryngectomy, create an airway lumen suitable for respiration, and, whenever possible, eliminate the need for a tracheostomy. [41-43] However, due to the postoperative swallowing and respiratory challenges and recurrence rates associated with extended hemilaryngectomy involving the cricoid cartilage, further refinement of the surgical technique is necessary.[44, 45]

Using vascularized, mucosa-covered tracheal grafts provides structural integrity and promotes long-term functional outcomes. Since its introduction by Dealare et al. in 1998, tracheal autotransplantation has demonstrated potential in complex airway reconstruction. [46] Attempts to reconstruct the airway using nonvascularized donor trachea grafts and synthetic implants have also been explored. Yet, these approaches have demonstrated significant limitations due to structural instability, poor integration, and high rejection rates. Despite the progress made in laryngeal preservation surgery, the challenge remains to develop more reliable and durable reconstructive techniques that can effectively restore airway function, maintain acceptable voice quality, and ensure long-term oncological control.[47-51]

Function-preserving techniques, such as extended vertical hemilaryngectomy with rotational thyrotracheopexy, provide an alternative reconstructive strategy. They prevent the need for total laryngectomy while preserving essential laryngeal functions and allow oncologically safe tumor resection while maintaining airway stability.[52,53]

1.4 The Role of 3D Modeling in Surgical Planning

Innovative surgical techniques, such as slide laryngotracheopexy and extended hemilaryngectomy with rotational crico-tracheopexy, require careful surgical planning, as the laryngeal framework and fundamental structure are significantly reconfigured during the procedure. Traditional imaging techniques, such as computed tomography (CT), magnetic resonance imaging (MRI), and endoscopy, provide valuable anatomical data but often fail to fully convey the three-dimensional spatial relationships of laryngotracheal structures due to the unique anatomical variability of the larynx. Since achieving a tension-free anastomosis is essential for optimal healing, improved visualization of airway pathology is critical. 3D modeling and printing have emerged as transformative tools, offering interactive, patient-specific representations that surpass the limitations of 2D imaging. As 3D printing technologies become widely accessible, healthcare professionals can integrate them into surgical planning and medical education. These technologies enhance preoperative visualization, personalized surgical planning, and hands-on training, benefiting various surgical fields, including otolaryngology, cardiovascular surgery, and alveodental procedures. [18,19, 60]

Historically, training in laryngotracheal surgery relied on cadaveric dissections, live surgeries, and synthetic models, each presenting significant limitations. While cadaveric specimens are anatomically accurate, they are costly, limited in availability, and fail to replicate the dynamic properties of living tissue. Synthetic models, though practical, lack patient-specific attributes and anatomical variability. [54] 3D-printed airway models provide a high-fidelity alternative, allowing surgeons to practice airway reconstructions, simulate rare and complex cases, and refine their techniques in a controlled and repeatable environment. [55,56] These models can be customized for specific pathologies, such as idiopathic subglottic stenosis, cricoid invasion by tumors, and post-traumatic airway deformities, ultimately enhancing surgical preparedness and precision.

As 3D technology evolves, future advancements will likely include AI-driven surgical planning tools, patient-specific bioengineered airway grafts, and real-time intraoperative 3D navigation systems. The growing affordability and accessibility of 3D printing and virtual surgical simulations suggest that these technologies will soon become a routine component of airway surgery and surgical training, further refining patient-centered treatment strategies and advancing the field of laryngotracheal surgery.[61]

The workflow presented in this thesis, utilizing CT and endoscopic image-based patient-specific 3D models of laryngotracheal pathology, enables more accurate assessments of stenotic regions, tumor infiltration, and structural proportions. Unlike conventional imaging, 3D models provide an interactive and precise representation of stenosis and tumor extension, allowing for detailed preoperative planning. In complex cases, such as extended laryngeal resections or advanced tracheal reconstructions, these models enable surgeons to simulate various surgical approaches, anticipate potential challenges, and refine their techniques before entering the operating room.

1.5 Thesis Objectives

Despite advancements in laryngotracheal surgery, critical challenges remain in achieving optimal long-term functional outcomes while minimizing the need for repeat interventions. This thesis aims to address these gaps by:

1. Evaluate the clinical outcomes and long-term effectiveness of slide laryngotracheopexy in iSGS management, focusing on airway patency, voice quality, and restenosis rates.
2. Assessing the oncological and functional results of extended vertical hemilaryngectomy with rotational thyrotracheopexy, analyzing its impact on airway stability, phonation, and swallowing function in patients with advanced glottic tumors.
3. Exploring the role of CT-based 3D modeling in preoperative planning and surgical education, emphasizing its potential to enhance precision, improve surgical outcomes, and facilitate skill acquisition.

By systematically analyzing these approaches, this study seeks to contribute to the refinement of function-preserving laryngotracheal surgery, offering improved treatment strategies for airway stenosis and laryngeal cancer patients.

2. Materials and Methods

2.1 Study Design

2.1.1. Patient Selection for Idiopathic Subglottic Stenosis (iSGS)

This retrospective case series included adult patients (≥18 years) diagnosed with idiopathic subglottic stenosis (iSGS). Eligible patients had Cotton-Myers grade II or higher stenosis, worsening dyspnea, or required a tracheostomy. Only those who had failed prior endolaryngeal or cricotracheal resection (CTR) interventions and were indicated for slide laryngotracheopexy were included.

The diagnosis was confirmed via endoscopy, with other potential causes such as autoimmune, traumatic, or iatrogenic factors—particularly prolonged intubation—systematically excluded by blood tests. HRCT was performed in all cases to assess the exact length of stenosis. Clinical history, previous interventions, and gastroesophageal reflux disease (GERD) were documented.

To rule out autoimmune involvement, blood tests for antineutrophil cytoplasmic antibodies (ANCA), specifically proteinase-3 (PR3) and myeloperoxidase (MPO), were conducted. IgG4 antibody levels were also measured to exclude IgG4-related disease.

2.1.2. Patient Selection for Extended Vertical Hemilaryngectomy with rotational thyrotracheopexy

This retrospective case series included adult patients with locally advanced glottic tumors that had invaded the anterior commissure and extended into the subglottic region. All included patients underwent histopathologic confirmation of malignancy, with detailed documentation of prior oncologic treatments and surgical interventions. The diagnosis was established based on preoperative microlaryngoscopic evaluation, CT imaging, and pathological findings.

2.1.3. Preliminary study of CT-based 3D laryngotracheal model printing

This preliminary study included patients of all ages and genders undergoing laryngotracheal surgery for advanced laryngeal cancer or cricotracheal stenosis. To ensure segmentation accuracy, patients with significant imaging artifacts, prior endolaryngeal or open-neck laryngotracheal surgery, or a history of tracheotomy were excluded. The study is intended to be expanded to a larger cohort for further validation.

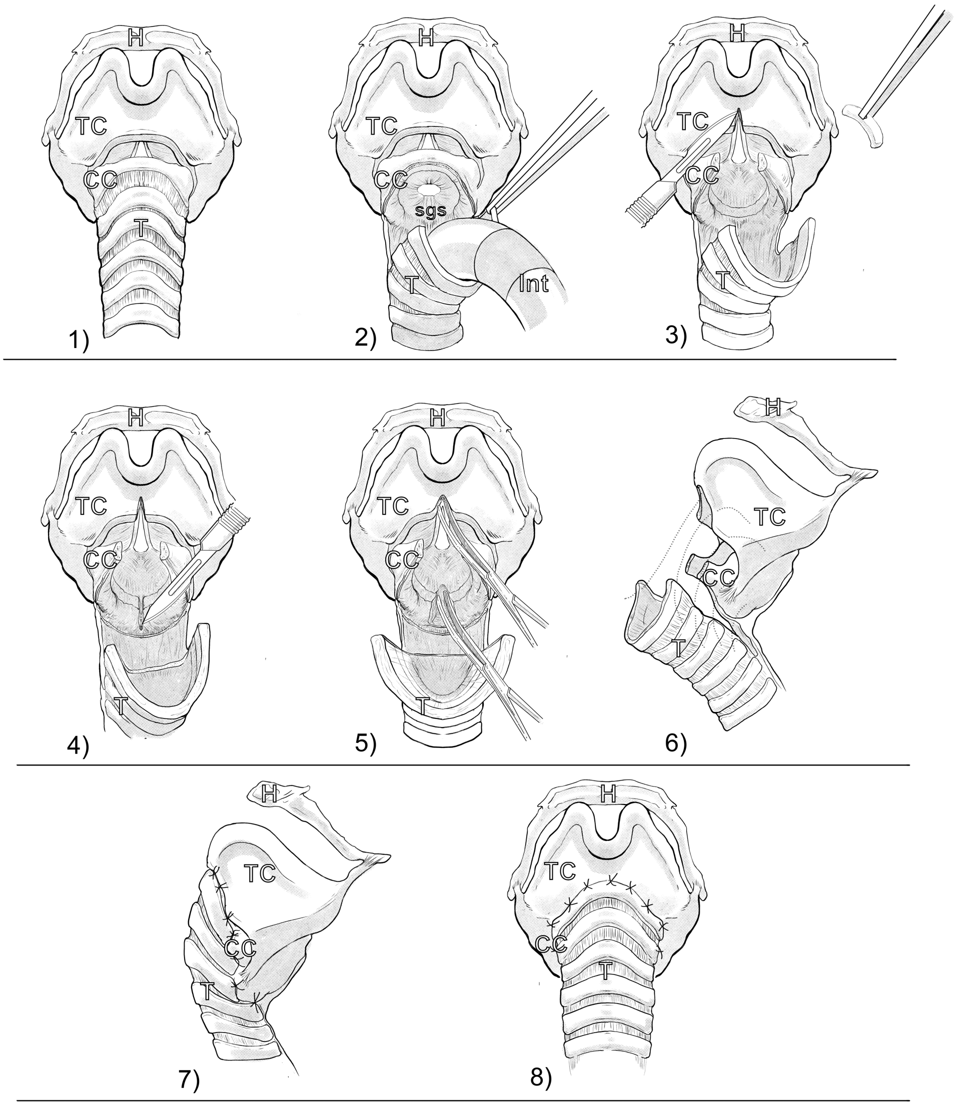
2.2 Surgical Techniques

2.2.1 Slide Laryngotracheopexy for iSGS

The procedure begins with a horizontal cervical incision at the level of the cricoid arch, allowing exposure of the larynx and trachea at the cricotracheal junction. A superior laryngeal release is then performed by incising the thyrohyoid membrane and dissecting the superior cornu of the thyroid cartilage. This is followed by circumferential dissection to separate the cricotracheal junction. Re-intubation is carried out directly into the trachea, after which an anterior midline laryngofissure is performed while preserving the soft tissues of the anterior commissure. Then, the cricoid arch is transected and expanded, and a midline laminotomy is executed on the posterior cricoid plate. Subsequent blunt dilation and separation of the cricoid halves are achieved using dissector forceps. Mobilization of the trachea is meticulously performed through atraumatic dissection using a sponge stick from the superior mediastinum. The membranous part of the trachea is carefully separated from the esophagus down to the level of the third to fourth tracheal cartilage. The posterior tracheal wall is then tailored to accommodate the necessary tracheal elevation, enabling the tracheal trunk to be repositioned against the posterior mucosa of the cricoid. Before proceeding with the anastomosis, a nasogastric tube is introduced.

For patients with a history of prior partial cricotracheal resection (PCTR), the surgical approach remains fundamentally unchanged, though certain modifications are required. If the anterior cricoid arch has been previously resected, the midline incision is made on the reconstructed anterior wall rather than on the cricoid arch itself. Since the trachea has already been elevated in these cases, special attention is directed toward ensuring adequate mobilization while preserving the integrity of the recurrent laryngeal nerves. Reconstruction of the anterior airway wall is achieved by interposing tracheal cartilage segments between the extended lamina of the thyroid cartilage and the cricoid, thereby creating a stable and sufficiently widened subglottic airway. The resultant airway lumen is significantly larger compared to its physiological state. The closure involves two double-armed continuous locked sutures, with knots secured externally. The sutures originate at the posterior midline and proceed in clockwise and counterclockwise directions until they converge at the anterior midline, forming a continuous suture ring. Following tracheal closure, the wound is closed in multiple layers by standard neck incision protocols, finally closing with intracutaneous skin sutures. A Redon drain (12 CH) with a vacuum-assisted wound drainage system is positioned at the midline. A cervical compression bandage is applied postoperatively to minimize tissue disruption within the pretracheal space during movement and limit excessive neck mobility. The steps of the surgical procedure are shown in Figure 1.

2.2.2 Rotational Crico-Thyrotracheopexy (RCTT) for Glottic Cancer

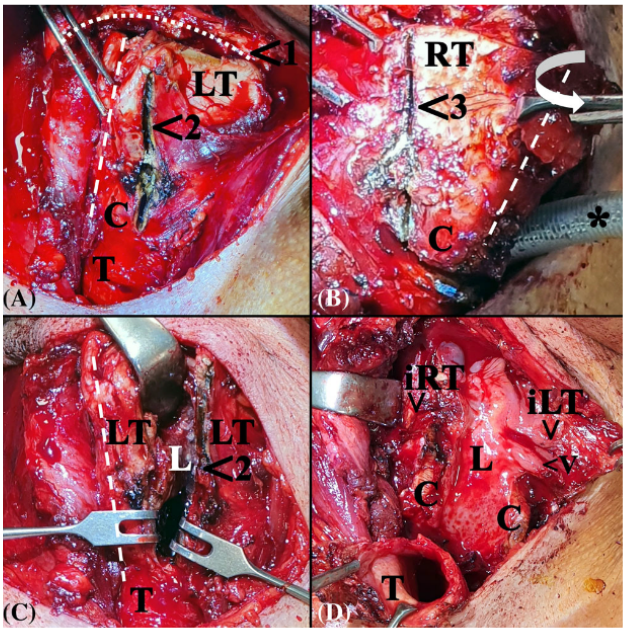


The surgical procedure commenced with a direct endoscopic evaluation of the airway

Figure 1. Schematic illustration of slide laryngotracheopexy. 1) Laryngotracheal complex is shown from below, ligaments are partially removed for better visual. 2) Dissection of the trachea 3) Excision of the cricoid arch and removal of scar tissue. Laryngofission is done below the level of the anterior commissure 4) posterior
Figure 2. Right-sided extended vertical hemilaryngectomy (intraoperative pictures, patient #2). LT, left thyroid ala;RT, right thyroid ala; C, cricoid cartilage; T, trachea; iLT, the inner surface of the remnant of left thyroid ala; iRT, the inner surface of the remnant of right thyroid ala; L, laryngeal lumen; V, remnant of the left vocal fold; 1: line of the suprathyroid incision; 2: incision of the thyroid and cricoid cartilage on the contralateral side of the tumor; 3: incision of the thyroid and cricoid cartilage on the ipsilateral side of the tumor; *endotracheal tube; white dashed line represents the midline of the larynx. (A) After the suprathyroid mobilization of the larynx, the LT and the cricoid cartilage is incised on the contralateral side of the tumor. (B) During the resection, only the posterior edge of the RT could be preserved. The larynx is rotated to the left. (C) The exploration of the laryngeal lumen. (D) The final stage of the resection after rightsided extended vertical partial laryngectomy.

to assess the extent of tumor infiltration. Microlaryngoscopy was performed under total intravenous anesthesia with supraglottic jet ventilation. Following endotracheal intubation, a horizontal incision was made at the level of the cricoid cartilage. Ipsilateral modified radical neck dissection, involving levels I–IV and VI, was carried out in all cases. Bilateral paratracheal neck dissection was also performed, with particular care taken to preserve the recurrent laryngeal nerve on the unaffected side. The trachea was then mobilized through careful dissection, allowing for its subsequent repositioning. The laryngotracheal complex was further explored by mobilizing the prelaryngeal muscles and dissecting the thyroid gland. (Figure 2 and 3)

Based on microlaryngoscopic findings, tumor removal was achieved through an



extended vertical partial laryngectomy. The strap muscles and thyrohyoid membrane were initially incised along the superior rim of the thyroid cartilage, and the superior horns of the thyroid cartilage were detached bilaterally to facilitate laryngeal release. Then, an anterior laryngofissure was performed using a monopolar needle knife or circular saw. The resection margin was extended 5–6 mm contralaterally to include the affected thyroid and cricoid cartilage portions. To ensure complete resection while preserving as much viable tissue as possible, both horizontal and vertical incisions were made on the ipsilateral thyroid ala, sparing the superior and posterior edges whenever feasible. The larynx was subsequently opened at the anterior incision line on the contralateral side, providing optimal visualization of the laryngeal lumen and tumor.

Further dissection involved peeling the piriform sinus from the posterior aspect, a critical step in preventing the formation of a pharyngocutaneous fistula. The resection specimen included the true and false vocal folds, the entire paraglottic space, the arytenoid cartilage, the thyroid ala, and the cricoid cartilage on the side of the lesion. In cases where tumor invasion extended to the cricoarytenoid joint or posterior commissure, a posterior medial incision was

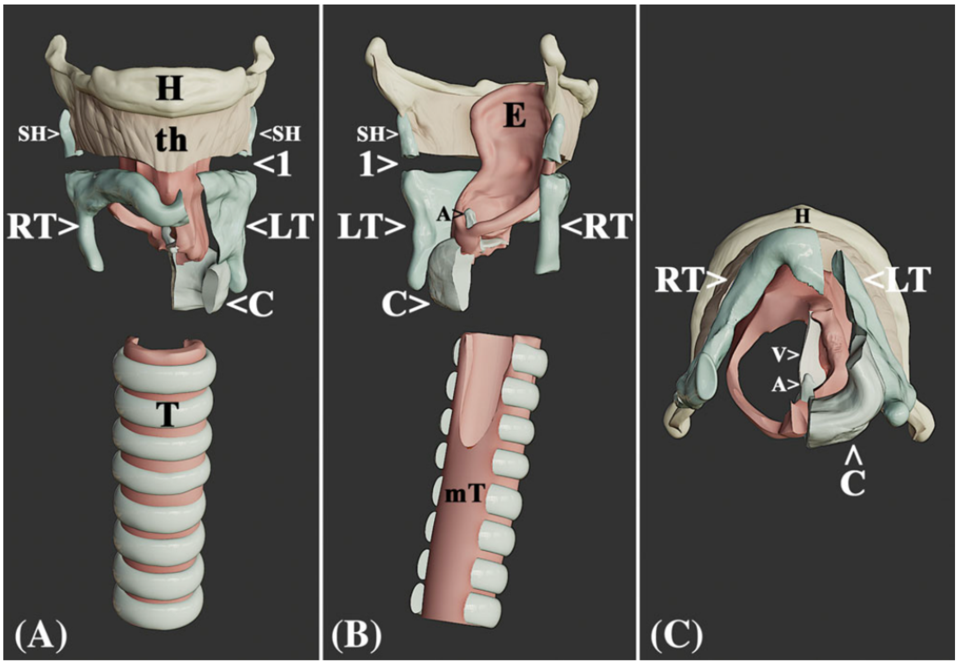


Figure 3. 3D model of the reconstruction by rotational cricothyrotracheopexy after right-sided extended vertical hemilaryngectomy. H, hyoid bone; th, thyrohyoid membrane; SH, superior horn of the thyroid cartilage; LT, left thyroid ala; RT, right thyroid ala; C, cricoid cartilage; T, trachea; E, epiglottis; mT, membranous wall of the trachea; V, left vocal fold. (A) The interposed tracheal graft maintains the cartilaginous framework of the larynx (anterior view). (B) The elevated and rotated tracheal flap stabilizes the supraglottic soft tissues as well (posterolateral view). (C) The C-shaped tracheal cartilages create a sufficiently wide glottic gap (superior view).

performed along the midline of the interarytenoid space. Every effort was made to preserve the integrity of the aryepiglottic fold. Further surgical steps were carried out only after a negative intraoperative frozen section confirmed clear margins. The ipsilateral portion of the pharyngeal constrictor muscle was preserved in all cases. Upon completion of the resection, the cricotracheal membrane was thoroughly dissected, and the orotracheal tube was repositioned directly into the trachea. A nasogastric feeding tube was also inserted. Subsequent reconstruction required further mobilization of the previously dissected trachea from the superior mediastinum. This was accomplished using blunt dissection along the natural tracheal wall plane. The length of the required graft was carefully assessed, after which the trachea was separated from the esophagus on the side of the laryngeal reconstruction. The mobilization extended to the fourth or fifth tracheal cartilage to ensure a tension-free anastomosis with the inferior margin of the thyroid and cricoid remnant. The membranous portion of the trachea was incised along the entire length of the laryngotracheal separation on the contralateral side of the lesion. At this stage, the distal trachea was repositioned superiorly and rotated by 90 degrees to facilitate the anastomosis. The direction of the rotation was determined by the side of the resection, with a clockwise movement for right-sided tumors (when viewed from above) and a counterclockwise adjustment for left-sided lesions. (Figure 4 and 5)

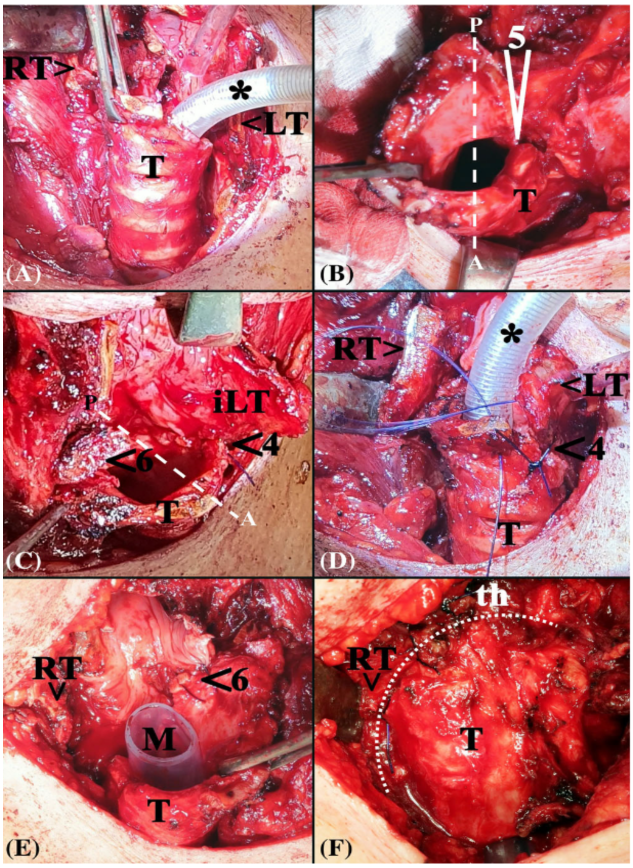


Figure 4. The steps of rotational crico-thyrotracheopexy (intraoperative pictures, [A–D]: patient #2; [E, F]: patient#6). LT, left thyroid ala; RT, right thyroid ala; T, trachea; iLT, the inner surface of the remnant of LT; th, thyrohyoid membrane; M, Montgomery T-tube; *endotracheal tube; 4: anterior cricotracheal anastomosis 5: incision/resection of the membranous wall of the trachea; 6: posterior cricotracheal anastomosis; the white dashed line represents the antero-posterior axis; dotted white line: line of the superior anastomosis in case of complete resection of the LT. (A) The trachea is mobilized and elevated. (B) The mobilized trachea is rotated and the membranous part of it is partially resected/incised depending on the size of the laryngeal defect. The dashed white line represents the antero-posterior axis. (C) First the posterior (6), then the anterior cricotracheal (4) anastomosis is sutured. (D) The inferior edges of the right and left thyroid remnants are sutured to the superior edge of the thyroid trunk, then the divided thyroid cartilage is reunited in the midline. (E) In patient #6, the LT was completely resected. The posterior cricotracheal anastomosis is sutured and a Montgomery T-tube is inserted for better mucosal healing. (F) After the anterior cricotracheal anastomosis, the superior edge of the trachea is directly sutured to the remnant of the RT, the thyrohyoid membrane and the hyoid bone.

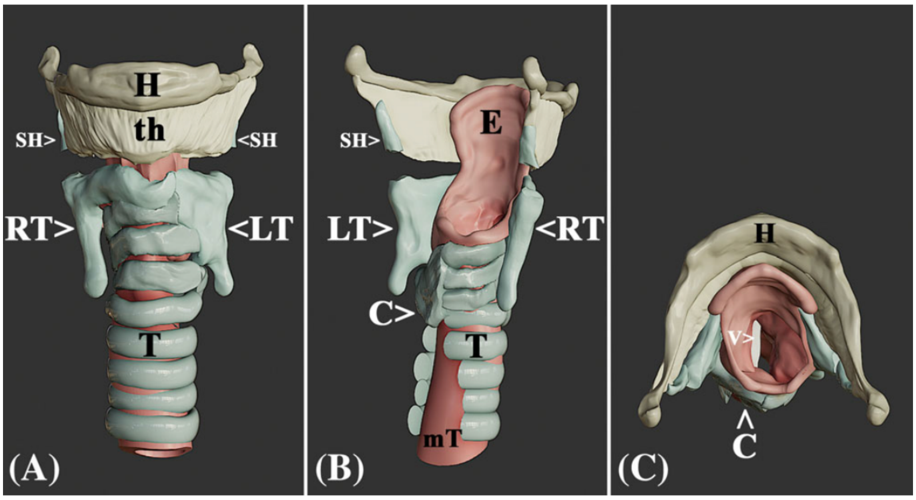


Figure 5. 3D model of the reconstruction by rotational cricothyrotracheopexy after right-sided extended vertical hemilaryngectomy. H, hyoid bone; th, thyrohyoid membrane; SH,superior horn of the thyroid cartilage; LT, left thyroid ala; RT, right thyroid ala; C, cricoid cartilage; T, trachea; E, epiglottis; mT, membranous wall of the trachea; V, left vocal fold. (A) The interposed tracheal graft maintains the cartilaginous framework of the larynx (anterior view). (B) The elevated and rotated tracheal flap stabilizes the supraglottic soft tissues as well (posterolateral view). (C) The C-shaped tracheal cartilages create a sufficiently wide glottic gap (superior view).

2.3 Application of 3D Modeling in Surgical Planning

Preoperative and postoperative high-resolution computed tomography (HRCT) scans in DICOM format were utilized for segmentation. Image processing was conducted using ITK-SNAP software to ensure precise visualization and differentiation of anatomical structures and pathological changes. Segmentation was manually performed by cross-referencing the CT images in axial, coronal, and saggital planes, with input from a radiologist specializing in head and neck anatomy to ensure accuracy. To facilitate detailed segmentation, specific anatomical regions were labeled, including the hyoid bone, thyroid cartilage, cricoid cartilage, trachea, glottis, epiglottis, aryepiglottic fold, and the area of tumor infiltration or stenosis. Preoperative laryngoscopic images were also referenced to enhance the accuracy of lesion localization and structural delineation. Segmentation was conducted on a MacBook Pro M1 workstation, with refinement carried out using a Wacom Cintiq 24 HD display tablet and a digital pen for improved precision in anatomical mapping (Figure 6).

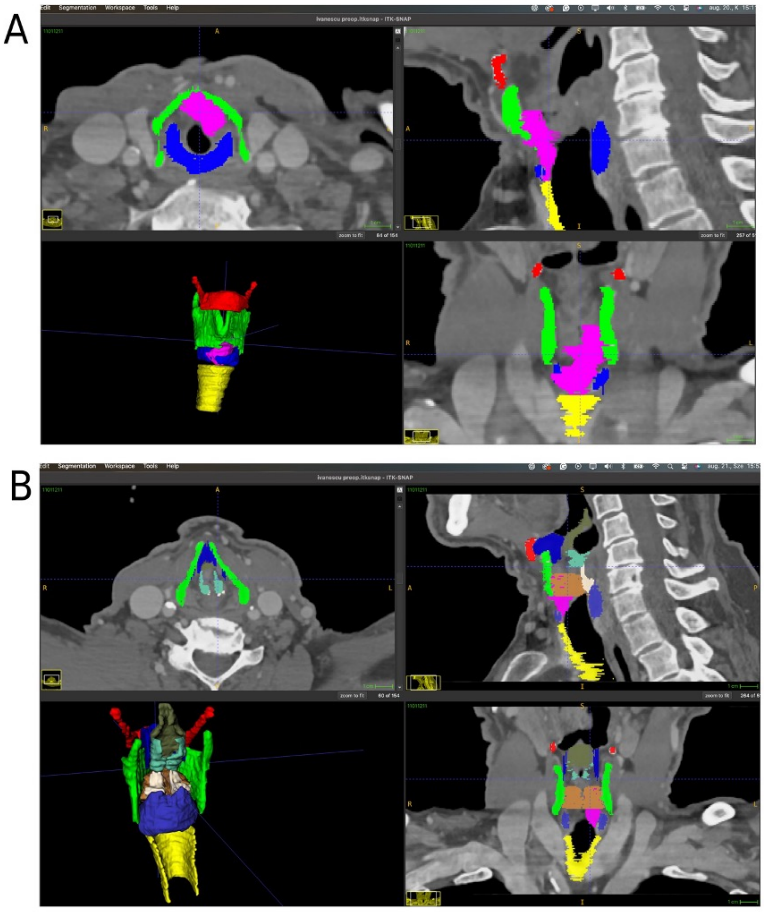


Figure 6. Screenshots of ITK Snap software during the manual segmentation process are shown in *Case 3.* Color legend: red – hyoid bone; green – thyroid cartilage; blue – cricoid cartilage; violet – tumor; light blue – epiglottis; brown – glottis; white – arytenoids; yellow – trachea. **A –** A generated 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.

2.3.1. Refinement Through 3D Digital Sculpting

Following segmentation, the mesh model was exported as an STL file and subjected to digital sculpting techniques to refine anatomical features. Refinement was performed using Nomad Sculpt software to smooth and adjust the mesh surface while maintaining anatomical fidelity. To enhance realistic interpretation, minimal modifications were applied to correct imaging limitations that could obscure fine anatomical details, such as the hyoid bone's anterior surface or the thyrohyoid membrane's fiber texture. Anatomical atlases were consulted to ensure anatomical consistency, particularly in regions where CT resolution was insufficient for detailed visualization. Critical areas, such as malignant tumors and stenotic segments, were highlighted to facilitate easier identification using distinct colors. This refinement was done on an Apple iPad Pro 12.9 with an Apple Pencil to enable precision modifications.

2.3.2. 3D Printing and Model Utilization

Two distinct 3D printing technologies were employed to generate physical anatomical models: Material Extrusion (MEX) and VAT photopolymerization (VPP) . The MEX process was conducted using a Voxelab Aquila 3D printer, with thermoplastic polyurethane (TPU) as the primary printing material. Print preparation and slicing were carried out using VoxelMaker software. For enhanced accuracy and flexibility, VPP printing was performed using a Form3 printer, employing Formlabs Flexible 80A resin. Print preparation for the VPP models was completed using specialized software platforms, including Preform and 3D Sprint. The process is shown briefly in Figure 7.

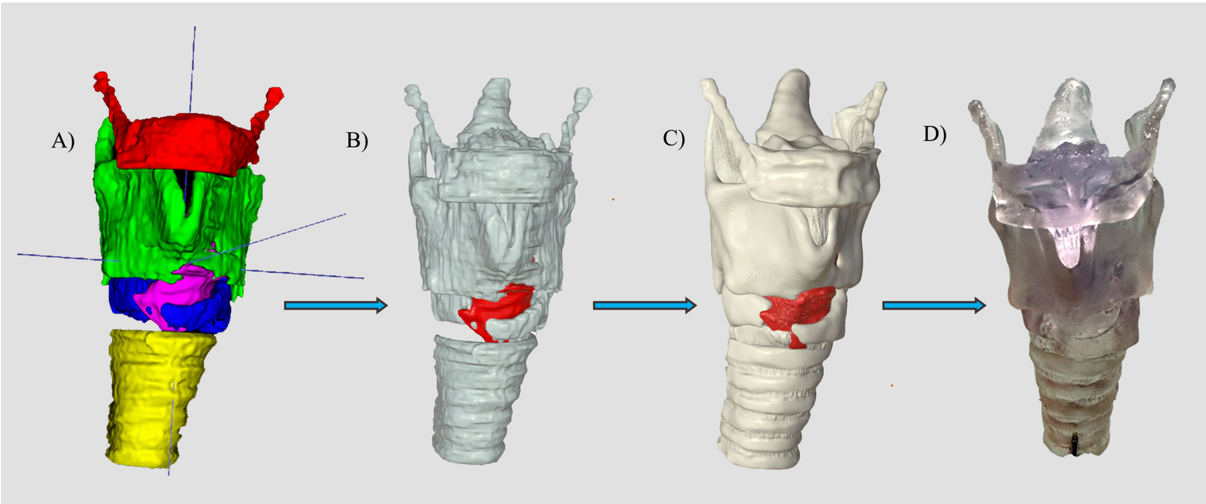


Figure 7.
A - 3D model generated by ITK Snap software based on the manual segmentation. Color legend: red – hyoid bone; green – thyroid cartilage; violet – tumor; blue – cricoid cartilage; yellow – trachea.
B - The generated 3D model is opened in Nomad Sculpt. Tumor extension is highlighted with red color.
C – The final virtual model after post-processing is shown. Tumor extension is highlighted in red color.
D- The VPP printed model based on the previous digital workflow.

2.4 Outcome Measures and Statistical Analysis

2.4.1. Postoperative care and functional evaluation after slide laryngotracheopexy

The functional outcomes of the surgery, including breathing, voice, swallowing, and overall patient satisfaction, were assessed six months postoperatively. Peak Inspiratory Flow (PIF) was measured using a Spirotube spirometer to evaluate respiratory function. Voice quality and swallowing ability were assessed through the Voice Handicap Index (VHI) and M.D. Anderson Dysphagia Inventory (MDADI) questionnaires were completed by patients during follow-up visits.

A standardized quality-of-life (QOL) questionnaire was used to evaluate postoperative symptoms, including dyspnea, noisy breathing, coughing, dysphonia, and dysphagia, with each parameter scored on predefined scales. Patient satisfaction was also recorded using a global assessment scale. [73]

To assess airway patency, a 70-degree rigid laryngoscopy was performed. Additional imaging or direct laryngotracheoscopy was conducted in cases where airway-related complications were suspected. Statistical analyses were performed using JASP software (version 0.17.3, JASP Team 2023).

2.4.2. Functional evaluation after extended partial laryngectomy with rotational thyrotracheopexy

Given the potential for progressive adverse effects following oncological therapy, functional outcomes were assessed at the end of each patient's follow-up period. Voice quality was evaluated using a previously established protocol based on the guidelines of the Committee on Phoniatrics of the European Laryngological Society. Acoustic parameters, including maximum phonation time, fundamental frequency, harmonics-to-noise ratio, jitter percentage, and shimmer percentage, were analyzed using Praat software (version 6.1.03, www.praat.org).

To assess voice-related quality of life, patients completed the Hungarian version of the Voice Handicap Index (VHI). Respiratory function was objectively evaluated by measuring Peak Inspiratory Flow (PIF). Subjective assessments of voice, breathing, swallowing, and overall postoperative satisfaction were collected using a standardized quality-of-life questionnaire. Particular attention was given to the swallowing function, with patients completing the M.D. Anderson Dysphagia Inventory (MDADI) to assess postoperative swallowing difficulties.

3. Results

3.1 Surgical and functional outcomes of slide laryngotracheopexy

Between December 2016 and December 2022, thirteen patients (two male and eleven female) diagnosed with idiopathic subglottic stenosis (iSGS) were enrolled in the study. The mean age was 59.3 ±16.7 years (range: 35–82). Detailed patient data is presented in Tables 1 and 2. Seven patients had already a tracheostomy at the time of initial assessment. HRCT scans revealed that the average longitudinal extent of stenosis was 17.2 ±7.2 mm. Four patients had previously undergone endolaryngeal laser surgery or balloon dilatation, while two had received partial cricotracheal resection (PCTR) at other institutions but experienced significant restenosis.

Patient/sex	Cotton-Myers grade	Stenosis length [mm]	Preoperative tracheotomy	Previous endolaryngeal interventions	Previous CTR
1 (F)	III	16.2	yes	0	0
2 (F)	III	14.2	no	3	0
3 (M)	IV	17.0	yes	0	0
4 (F)	II	16.5	no	0	0
5 (F)	II	14.9	yes	0	0
6 (F)	III	6.0	no	1	1
7 (M)	III	25.0	yes	0	0
8 (F)	III	20.0	no	0	0
9 (F)	II	22.5	no	0	0
10 (F)	III	10.0	no	10	0
11 (F)	III	8.3	yes	0	1
12 (F)	III	33.0	no	0	0
13 (F)	II	19.8	no	2	0

Table 1. Detailed patient data. F=female; M=male; CTR=Cricotracheal Resection

All patients were extubated in the operating room following surgery, and none required intensive care unit (ICU) admission. The average removal time for the surgical drain and nasogastric feeding tube was five and eleven days postoperatively, respectively. One patient (case #11) experienced postoperative dyspnea due to excessive airway crusting on the fifth day, necessitating temporary re-tracheotomy. This complication, caused by impaired secretion clearance, was managed with inhalation therapy, and the patient was successfully decannulated after five days. No necrosis was observed at the level of the anastomosis or tracheal mucosa, and no other major complications occurred during hospitalization. The average length of hospital stay was fourteen days. Due to granulation tissue formation, three patients required adjuvant CO_2 laser vaporization within one year. All of them had preoperative tracheotomies performed at other institutions. In one case (patient #6), mild granulation at the anastomotic site was observed in the first postoperative month, necessitating a single topical mitomycin-C application. This patient had also previously undergone PCTR surgery. No further surgical interventions, including repeat open-neck procedures were required.

Patient	Sex	Age [years]	GERD	Smoking
1.	female	82	no	non smoker
2.	female	76	no	non smoker
3.	male	33	no	non smoker
4.	female	42	no	non smoker
5.	female	76	yes	non smoker
6.	female	54	yes	non smoker
7.	male	76	no	smoker
8.	female	56	no	non smoker
9.	female	35	no	non smoker
10.	female	53	yes	non smoker
11.	female	50	no	non smoker
12.	female	74	yes	non smoker
13.	female	64	yes	non smoker

Table 2. Detailed patient data. (GERD=Gastro-esophageal Reflux Disease)

All patients demonstrated adequate airway function and optimal breathing during the follow-up period. No cases of recurrent laryngeal nerve injury-related laryngeal paralysis were recorded. Peak Inspiratory Flow (PIF), Quality of Life (QoL), Voice Handicap Index (VHI), and M.D. Anderson Dysphagia Inventory (MDADI) scores are summarized in Table 3.

The minimum, maximum, and mean follow-up durations were 12, 84, and 41 months, respectively. Patient conditions before inclusion and postoperative events are detailed in Figure 8, while pre- and postoperative endoscopic images are shown in Figure 9.

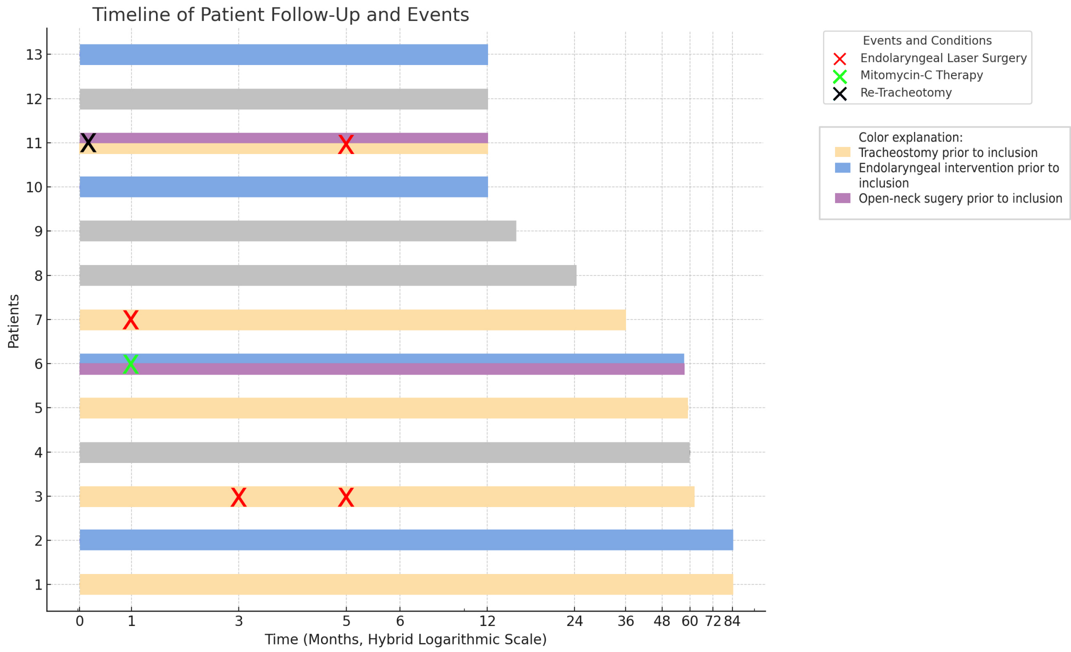


Figure 8. Timeline of patient follow-up and events

	QoL	PIF [l/s]	MDADI	VHI
Mean	9.00	2.76	95.61	18.69
Std.Deviation	2.16	0.83	4.335	13.35
Minimum	6.00	1.85	86.21	7.00
Maximum	13.00	4.25	100.00	53.00

Table 3: Postoperative functional results of surgery. QoL: Quality of Life; PIF: Peak Inspiratory Flow; MDADI: MD Anderson Dyphagia Inventory; VHI: Voice Handicap Index

QoL - higher value represents better result; MDADI - value over > 80 indicates minimal to no impact on quality of life; VHI ≤ 10-15 indicates minimal to no perceived handicap.

Following nasogastric tube removal, patients were transitioned to an oral diet with gradual advancement from pureed to solid food. At the time of the final follow-up, all patients remained decannulated with satisfactory respiratory function.

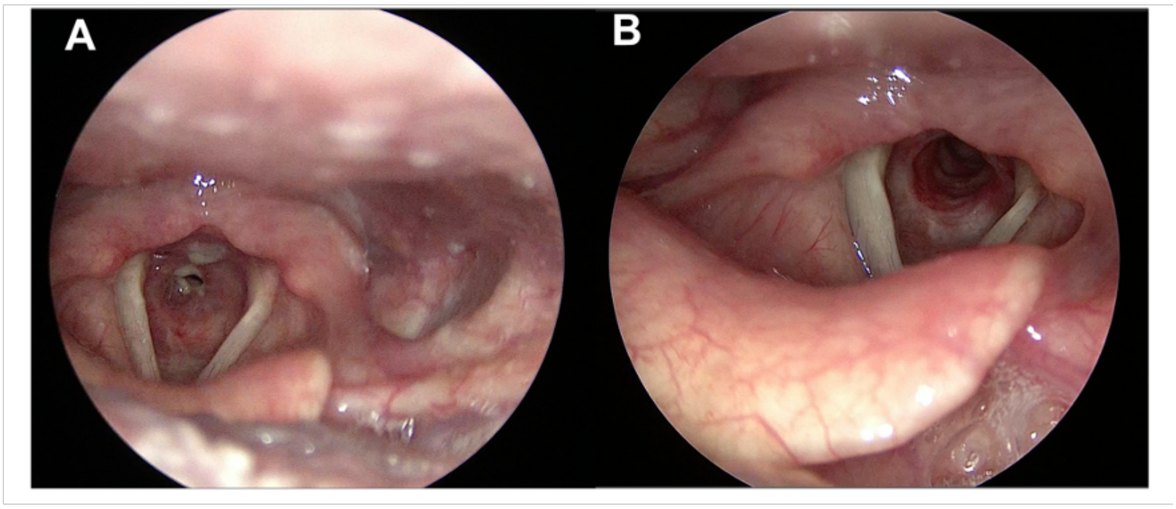


Figure 9. Endoscopic pictures of patient #13.
A: preoperative Cotton-Myer grade III subglottic stenosis.
B: Subglottic lumen in the 6th postoperative month.

3.2 Outcomes of Rotational Thyrotracheopexy

Extended vertical partial laryngectomy was performed in eight patients (six males, two females) with a mean age of 58 years (range: 48–75 years) for vocal fold malignancies involving the anterior commissure and subglottis. All patients exhibited unilateral or bilateral vocal fold motion impairment preoperatively. In cases #1, #3, and #5, tumor extension reached the posterior commissure, while contralateral spread was noted in cases #1, #2, and #7. Tumor involvement extended into the supraglottic region in four cases, with case #4 presenting the most extensive infiltration, affecting the first two tracheal rings. Tumor extent was assessed preoperatively through computed tomography (CT) or magnetic resonance imaging (MRI). Additional patient data are detailed in Table 4.

Patient/ age/sex	#1/57 years /m	#2/52 years /m	#3/48 years /m	#4/75 years /f	#5/63 years /m	#6/59 years /m	#7/61 years /m	#8/49 years /f
Max. diameter of the tumor	32 mm	30 mm	27 mm	35 mm	28 mm	17 mm	35 mm	25 mm
Extension of the tumor	LVF, anterior quarter of the RVF, AC, PC, ipsilateral SG	RVF, AC, bilateral SG	RVF, RFVF,AC, PC, ipsilateral SG	RVF, AC, Ipsilateral thyroid ala, the first two tracheal cartilage	LVF, AC, PC, ipsilateral SG	LVF, LFVF, AC, ipsilateral SG	RVF, RFVF, AC, anterior quarter of LFVF, ipsilateral SG	RVF, AC, RFVF, ipsilateral SG, AC
Vocal fold mobility	Left-sided impairment	bilateral impairment	right-sided immobility	right-sided impairment	left-sided immobility	left-sided impairment	right-sided immobility	right-sided impairment
Histology	high-grade leimyosarcoma	moderately differentiated SCC	well-differentiated SCC	Hürthle cell carcinoma	well-differentiated SCC	moderately differentiated SCC	well-differentiated SCC	moderately differentiated SCC
Previous surgery	laser cordectomy (type III)	laser cordectomy (type III)	MLS, tracheotomy	MLS, laser debulking	MLS	MLS	MLS	MLS

Table 4. Detailed patient data. Abbreviations: AC, anterior commissure;f, female;LFVF, left false vocal fold;m, male;MLS, microlaryngeal surgery;PC, posterior commissure; RFVF, right false vocal fold;RVF, right vocal fold;SCC, squamous cell carcinoma; SG, subglottis

Two patients (cases #1 and #2) had previously undergone European Laryngological Society Type III laser cordectomy at another institution before requiring open partial laryngectomy. Patients #3 and #4 presented with severe dyspnea and required tracheotomy and laser debulking before definitive surgery. Histopathological analysis confirmed squamous cell carcinoma in six cases, poorly differentiated leiomyosarcoma in case #1, and Hürthle cell thyroid carcinoma in case #4, which developed eight years after total thyroidectomy and radioiodine therapy.

No major perioperative or postoperative complications were observed. Postoperative details are summarized in Table 5. The Montgomery T-tube was removed under general anesthesia between the 6th and 13th postoperative days, with definitive decannulation immediately feasible in five cases. The remaining three patients were successfully decannulated within four days of stent removal. Oral feeding was initiated progressively between 7 and 20 days postoperatively, and all tracheostomies closed spontaneously.

Permanent histopathology confirmed tumor-free resection margins in all cases. Due to the advanced stage of their malignancies, all patients except case #4 underwent adjuvant radiotherapy following Hungarian oncology protocols. Case #4 did not require further oncological treatment. Postoperative CO_2 laser vaporization was necessary in two cases (#4 and #8) during the 11th and 14th postoperative weeks to manage anterior commissure synechiae causing dyspnea. (Figure 10). No further airway interventions were needed for the remaining patients.

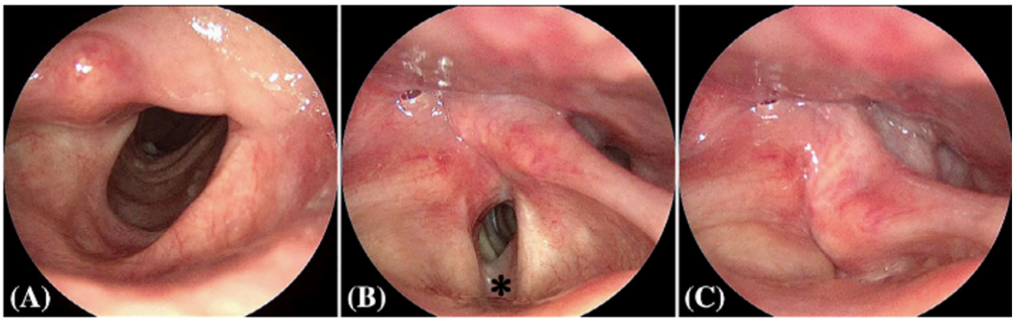


Figure 10. Postoperative endoscopic pictures (sixth postoperative months) A)the interposed tracheal graft on the left side proveides an appropriate airway (patient#6) B) A mild subglottic synechia was observed (*) beneath the former anterior commissure (patient#4). The active movements of the preserves ledt vocal fold ensure a good phonatory closure (patient#4)

During follow-up, patient #1 developed pulmonary metastatic leiomyosarcoma by the fourth postoperative month and underwent multimodal oncologic therapy. However, no local

Patient/age/sex	#1/57 years/m	#2/52 years/m	#3/48 years/m	#4/75 years/f	#5/63 years/m	#6/59 years/m	#7/61 years/m	#8/49 years/f
Removing of the Montgomery T-tube (postoperative day)	8	7	7	6	7	12	12	13
Decannulation (postoperative day)	8	7	8	6	11	13	12	13
Oral feeding (postoperative day)	9	9	9	7	12	14	20	15
Length of hospitalization (day)	17	12	13	13	16	23	21	16
Additional intervention (postoperative week)	-	-	-	Laser MLS (11)	-	-	PEG (8)	Laser MLS (14)

Table 5. Postoperative care after rotational crico-thyrotracheopexy. Abbrevations: f, female, m, male;MLS, microlaryngeal surgery;PEG

or regional recurrence was detected during a 51-month follow-up. Patient #4 died due to acute myocardial ischemia in the seventh postoperative month, with an autopsy confirming the absence of recurrent malignancy.

The follow-up duration for patients #2, #3, #5, #6, #7, and #8 ranged between 11 and 50 months, during which all remained free from local or distant recurrence and were able to resume premorbid activities of daily living. All patients reported a socially acceptable voice. Oral feeding without dietary restrictions was maintained in seven patients, while patient #7 required percutaneous endoscopic gastrostomy (PEG) placement due to difficulties ingesting solid foods (Table 5). Postoperative functional results are detailed in Table 6.

Patient/age/sex	#1/57 years/m	#2/52 years/m	#3/48 years/m	#4/75 years/f	#5/63 years/m	#6/59 years/m	#7/61 years/m	#8/48 years/f	Range
Mean fundamental frequency (Hz)	128.3	142.5	90.2	99.1	106.5	92.8	138.9	101.2	f:155-334; m: 85-196
Mean phonation time	4.1	2.8	5.1	4.4	4.9	3.0	3.9	3.3	15<
Jitter(%)	10.3	7.7	9.4	1.5	10.3	6.0	9.9	8.9	<1.04
Shimmer (%)	17.0	14.3	12.2	18.9	17.4	13.5	22.9	15.0	<3.81
Harmonics-to-noise radio (dB)	1.9	5.4	2.3	2.0	4.7	4.3	1.6	2.9	20<
VHI	15	29	44	21	52	58	26	75	0-120
MDADI	94.7	95.8	98.9	92.6	88.4	94.7	PEG	86.3	0-100
PIF (l/s)	1.5	1.5	3.1	2.6	1.7	3.3	2.0	1.3	-
QoL	7	8	8	8	11	7	13	17	6-25
Follow-up (months)	51	50	47	6	48	22	15	11	

Table 6. Postoperative funcional results. Abbrevations: f, female;m, male;MDADI, M.D. Anderson Dysphagia Inventory; VHI, Voice Handicap Index;PIF, Peak Inspiratory Flow;Qol, Quality of Life;PEG, Percutanous endoscopic gastrostomy.

3.3 3D Model Utilization and Impact on Surgical Planning

We applied the workflow to three clinical cases to refine our CT-based 3D modeling and printing methodology, progressively improving its accuracy and utility. Table 7 provides detailed patient data.

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

Table 7. Detailed patient information.

Case 1: Virtual Modeling for Surgical Planning and Education

The first case involved a patient with advanced T3 glottic carcinoma who underwent extended partial laryngectomy with rotational tracheopexy. Segmentation was performed using preoperative and postoperative HRCT images and digital post-processing. The resulting virtual

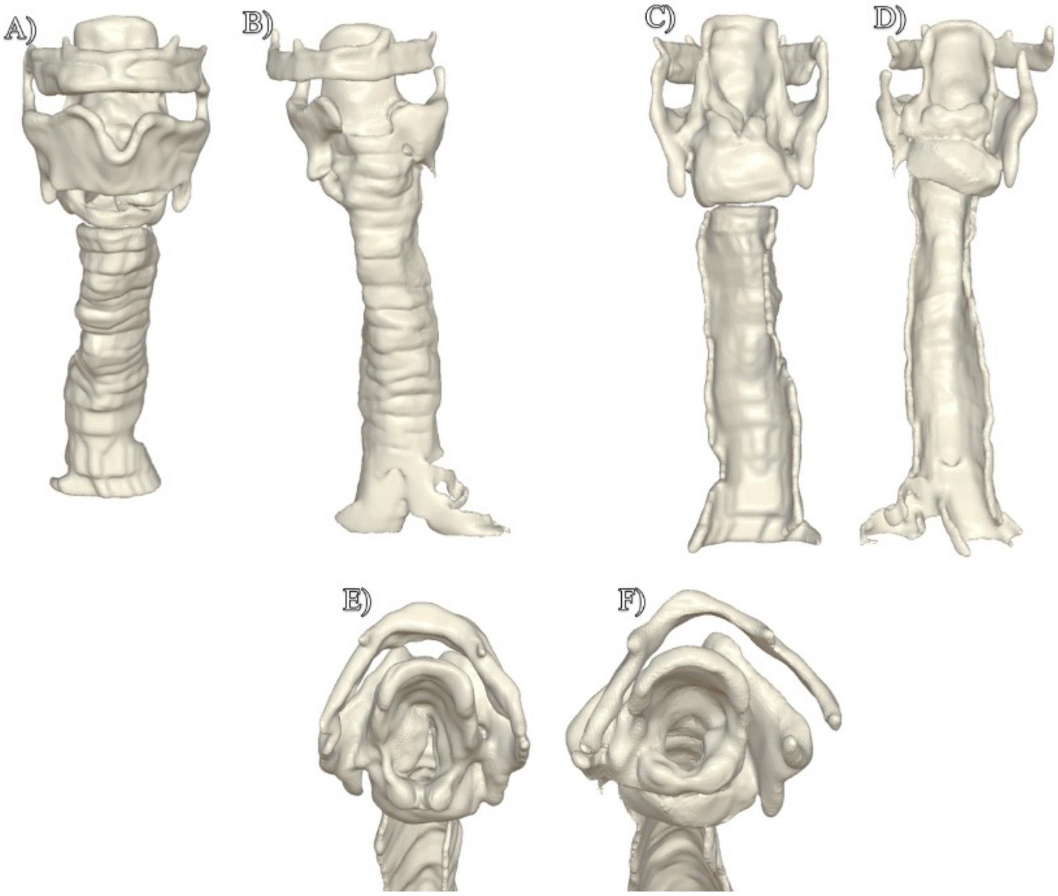


Figure 10. Virtual interpretation of pre-and postoperative laryngotracheal anatomy after extended hemilaryngectomy with rotational thyro-tracheopexy in *Case 1*.A, B – Pre- and postoperative model from frontal view after digital post-processing. C, D – Pre-and postoperative model from back view after digital post-processing. E, F – Pre- and postoperative model from superior view after digital post-processing.

model was used for graduate medical education (5th-year students), professional surgical training, and presentation at the National Otolaryngology Congress. This case validated the feasibility of virtual 3D models in surgical planning and medical training. Results are shown in Figure 10.

Case 2: First Physical 3D Printed Model

Building on the success of virtual modeling, the second case marked our first attempt at physical 3D printing. The patient, diagnosed with idiopathic subglottic stenosis, underwent slide laryngotracheopexy, and a corresponding 3D model was generated. The goal was to assess material feasibility and anatomical accuracy. The model was printed at a 1:1 scale using the MEX printing technique with thermoplastic polyurethane (TPU). While the model successfully represented the airway structures, several limitations emerged. The low print resolution (XY: 100 µm / Z:300 µm with TPU filament diameter 1,75mm) resulted in reduced anatomical detail, and the TPU material lacked the softness and pliability necessary for surgical simulation. The process is shown in Figure 11. However, suturing tests on the printed structure were promising, as the material allowed for stable suture placement without tearing. The model was incorporated

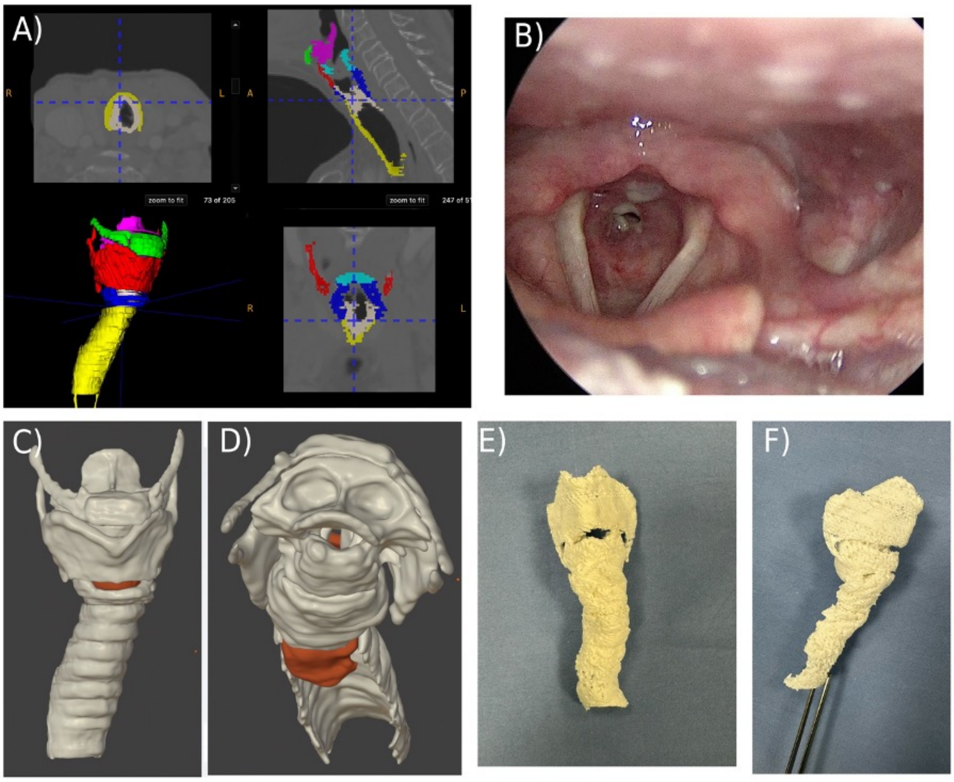


Figure 11. Steps and materials used during the creation of the preoperative 3D model in *Case 2.* A – The preoperative CT image and the segmentation process are shown. Color legend: green – hyoid bone; red – thyroid cartilage; dark blue – cricoid cartilage; light blue – glottis; violet – epiglottis; 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.

into a head-neck mannequin setup, covered with a silicone sheet simulating skin, enabling a realistic surgical workflow simulation. Despite the rigidity of the material and the printer's limitations, the process was a proof-of-concept highlighting the need for softer, more flexible materials and more refined printing techniques. Steps of the surgery are shown in Figure 12.

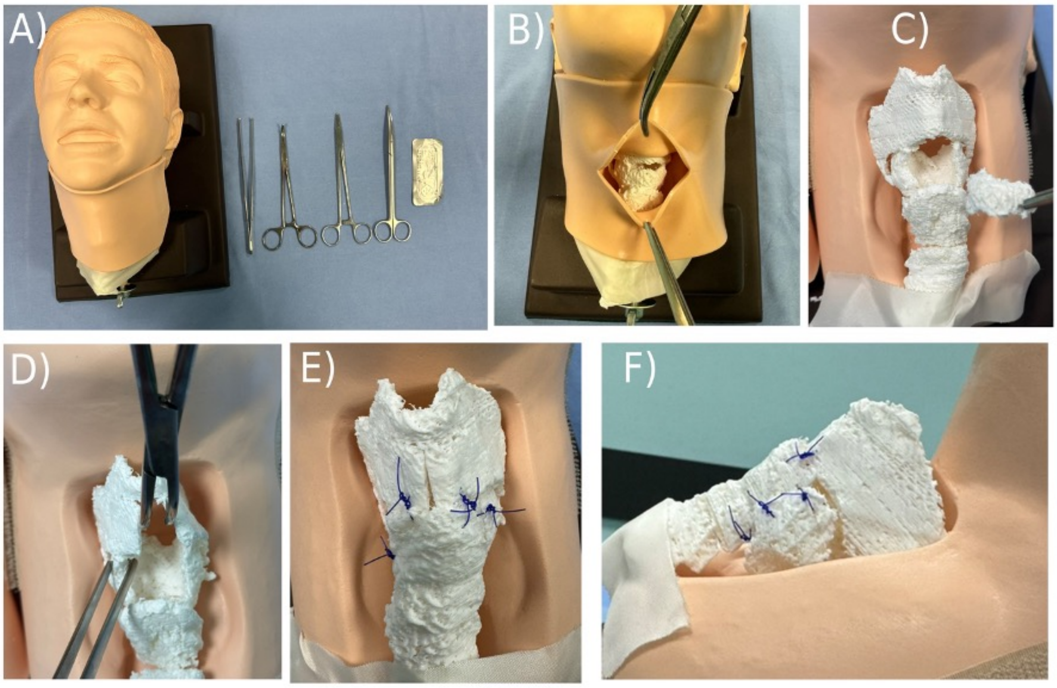


Figure 12. The preoperative 3D model of Case 2 was printed with MEX printing technique using TPU filament. A – The head-neck mannequin is shown with the surgical instruments. The printed model is placed in the socket of the neck part and covered with a silicone sheet. B – The silicon sheet is incised 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.

Case 3: Advancing to VPP Printing for Enhanced Realism

To overcome the limitations identified in Case 2, we collaborated with 3D printing specialists and transitioned to VAT photopolymerisation (VPP) printing using Formlabs Flexible 80A resin. The printing resolution was 100 µm for the Z-axis (layer height) and 25 µm for the XY-axis. This material was chosen for its superior surgical applicability, allowing for suture placement, incisions, and resection simulations. Steps and results are shown in Figure 13.

A preoperative virtual model was prepared for Case 3, representing a T3 glottic carcinoma with cricoid arch invasion. The final VPP-printed model demonstrated excellent anatomical accuracy, with remarkable cartilaginous and soft tissue structures. The flexibility of the resin enabled realistic surgical manipulation, providing a hands-on intraoperative experience. The final model was validated within the same mannequin-based surgical setup, where it was subjected to simulated surgical procedures. Surgeons reported that the VPP-printed

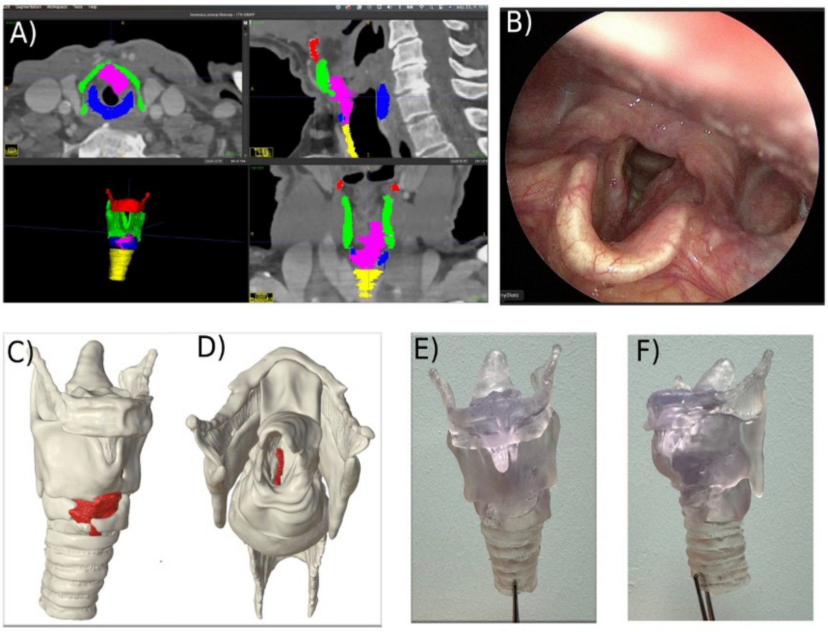


Figure 13. The creation of the preoperative laryngotracheal 3D model is shown in Case 3. A – The manual segmentation is shown with the corresponding CT images. Color legend: red – hyoid bone; green – thyroid cartilage; violet – tumor; blue – cricoid cartilage; yellow – trachea. B – Preoperative endoscopic 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.

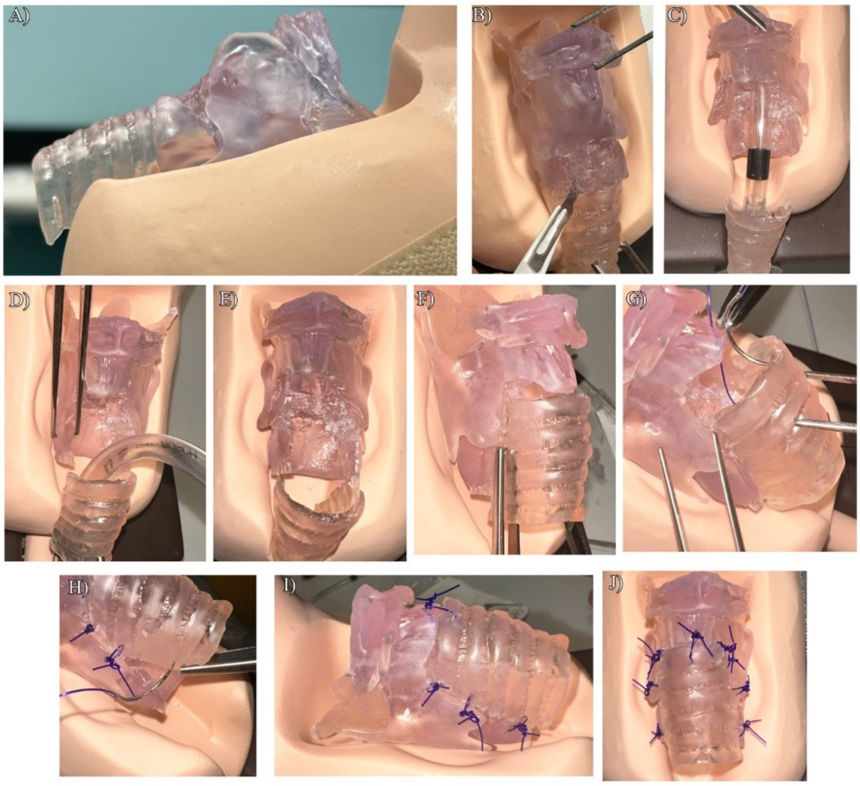


Figure 14. VPP printed model of *Case 3* is shown with the simulated surgical steps of extended hemilaryngectomy with tracheopexy. A – The laryngotracheal model is placed in the socket of the training mannequin. B – Incision is done on the cricoid arch. C – Tube placement is simulated after the dissection 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.

model closely mimicked actual surgical conditions, confirming its potential for preoperative planning and advanced surgical education.

Compared to previous cases, this iteration represented a significant improvement, emphasizing the importance of iterative refinement in medical 3D printing. Steps of the surgery are shown in Figure 14. We evaluated the model's realistic aspect by comparing specific surgery steps to intraoperative images. Comparison is shown in Figure 15.

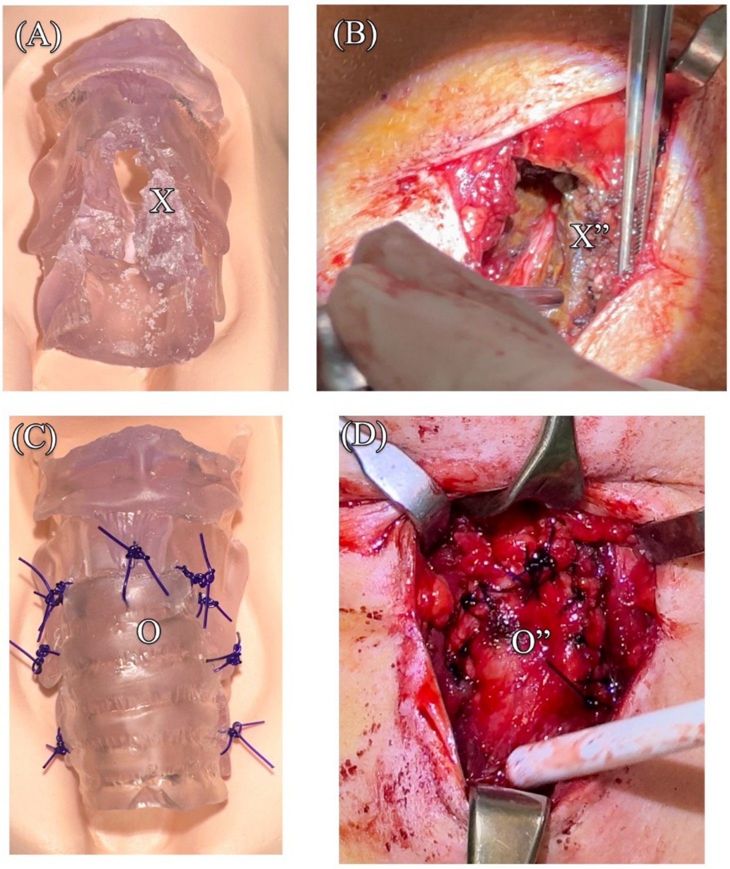


Figure 15. The comparison of the laryngotracheal model and the intraoperative surgical status of Case 3. A – VPP printed laryngotracheal model from the frontal view. B – Intraoperative photo of Case 3 during the resection of the tumor. X and X ''represent identical parts of the thyroid lamina with tumor 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.

4. Discussion

4.1 Idiopathic Subglottic Stenosis: Pathogenesis, Diagnosis, and Surgical Management

Idiopathic subglottic stenosis (iSGS) is a rare condition characterized by the progressive narrowing of the subglottic airway. Its diagnosis primarily relies on excluding other potential causes, including autoimmune disorders, vascular anomalies, iatrogenic trauma, malignancies, and post-intubation injuries. Although c-ANCA antibodies have been detected in some instances, their presence is inconsistent, and no definitive autoimmune correlation has been established. Moreover, while iSGS is not recognized as a hereditary disease, familial occurrences have been reported, suggesting a potential genetic predisposition.[62]

The underlying pathophysiology of iSGS involves fibroblast hyperproliferation and excessive extracellular matrix deposition, driven by IL-23 and IL-17A signaling pathways. These cytokines promote the activation of TGF-β and MMP9, leading to progressive airway fibrosis. Compared to post-intubation stenosis, iSGS shows elevated INF-γ expression, highlighting differences in immune-mediated responses.[63] Despite these molecular insights, no approved biological therapy currently exists for iSGS. In this study, the condition predominantly affected patients in late adulthood, and no cases of juvenile asthma or misdiagnosed COPD were identified.

iSGS is significantly more prevalent among women, prompting hypotheses regarding the role of estrogen in abnormal inflammatory and fibrotic processes. However, studies have not demonstrated increased expression of estrogen and progesterone receptors in affected tissues, leaving the hormonal contribution uncertain. In this study, none of the patients had a history of smoking or COPD, but a significant proportion had gastroesophageal reflux disease (GERD). Given the potential impact of pepsin-mediated mucosal injury, GERD is considered a contributing factor to chronic airway inflammation in iSGS. [64,65]

A widely accepted mechanical theory of iSGS pathogenesis is the "telescope phenomenon," which describes chronic mechanical stress on the airway during coughing. Repeated contraction of the tracheal musculature and frictional forces at the cricoid level may lead to venous congestion, chronic inflammation, and fibrosis of the subglottic region. The first tracheal ring is particularly vulnerable due to its structural position, as it may shift within the cricoid framework during coughing, resulting in repeated mucosal injury. Additionally, the vascular architecture of the cricoid cartilage, characterized by a dual-layered plexus of superficial and deeper vessels, may contribute to its susceptibility to chronic inflammation. Slide laryngotracheopexy offers a structural solution by bypassing the anterior cricoid with a tracheal flap, thus reducing mechanical stress and the likelihood of recurrent fibrosis. [66-68]

There is no universally accepted treatment protocol for iSGS, and surgical strategies vary based on institutional expertise and disease severity. Currently, balloon dilation and CO_2 laser excision are the most frequently employed endolaryngeal interventions. These procedures are effective for mild stenosis (Cotton-Myer I-II, with stenotic lengths <1 cm) but are insufficient for more advanced cases (Cotton-Myer III-IV), where recurrence rates remain high. An innovative approach, the Maddern procedure, integrates endolaryngeal shaver resection followed by buccal mucosal grafting supported by a temporary silicone stent. While promising, this method requires further validation in long-term studies. [5,6,69]

For more extensive stenoses, multiple endolaryngeal interventions can lead to hourglass deformities, as thermal coagulation damages surrounding tissue. Cricotracheal resection (CTR) offers a more definitive solution with lower recurrence rates, but it carries higher perioperative risk and functional morbidity, particularly concerning voice outcomes. Many CTR candidates already have a history of tracheostomy or multiple prior endolaryngeal procedures, further complicating postoperative recovery.

To mitigate restenosis, a multimodal strategy combining endolaryngeal and open-neck surgery with local adjuvant therapies, such as topical mitomycin-C, is often necessary. The demand for a reliable, function-preserving open surgical technique remains high, particularly among younger, active patients who seek alternatives to tracheostomy-dependent lifestyles. [11,12,20]

The cricoid cartilage plays a central role in maintaining the structural integrity of the larynx. Conventional partial cricotracheal resection (PCTR) involves end-to-end anastomosis between the cricoid arch, trachea, and thyroid cartilage lamina, sometimes requiring rib cartilage grafts or stent placement for additional support. While effective, these approaches introduce secondary donor-site morbidity, increased infection risks, and potential anastomotic complications due to tissue fragility. [70-72]

Slide laryngotracheopexy presents a novel approach that modifies the anastomotic geometry to create a wider, more stable subglottic airway. By using a side-to-end anastomosis rather than a conventional end-to-end configuration, the technique preserves more native cartilage, reducing the likelihood of anastomotic failure and restenosis. The tracheal flap, which includes vascularized mucosa, facilitates optimal wound healing and mucociliary clearance, thereby improving long-term airway stability. Furthermore, the elliptical orientation of the anastomosis minimizes horizontal rotational forces, decreasing the risk of mechanical trauma and dehiscence. The increased suture perimeter distributes tension more evenly, potentially improving postoperative stability. A fundamental challenge in airway reconstruction is balancing structural stability with functional preservation. Maintaining arytenoid mobility and intact sensory innervation is crucial for preventing aspiration. Unlike PCTR, slide laryngotracheopexy spares the cricoid plate, ensuring the preservation of interarytenoid dynamics and maintaining sufficient airway clearance mechanisms. [26-28]

Postoperative evaluations in this study confirmed stable airway function with minimal aspiration risk. Based on MDADI questionnaire results, patients exhibited good swallowing function, likely due to the preservation of key laryngeal structures. [73] Voice outcomes were also favorable, as the procedure maintains the anterior commissure and vocal cords, ensuring adequate phonation.

According to the literature, postoperative care requirements for slide laryngotracheopexy do not differ significantly from those of conventional CTR. However, complications were more prevalent in patients with prior tracheotomy and multiple endolaryngeal interventions, likely due to altered tissue regenerative capacity, compromised blood supply, and local microbiome disruption. In such cases, scar formation and impaired mucociliary function contributed to postoperative airway secretion-related complications. PIF and endoscopic assessments confirmed the long-term patency of the subglottic space following slide laryngotracheopexy, with minimal restenosis risk. Based on QoL and MDADI outcomes, patient satisfaction remained high, and recurrent nerve injury was not observed.

Overall, this technique demonstrates significant potential as a function-preserving alternative to conventional cricotracheal resection, offering a balance between airway stability, phonation quality, and swallowing function.

4.2 Surgical Management of Advanced Laryngeal Cancer: Challenges and Reconstructive Approaches

The treatment of advanced laryngeal cancer, particularly in cases with a progression to glottic-subglottic regions impairing vocal fold mobility and malignancies infiltrating the anterior commissure and invading the thyroid and cricoid cartilage, remains a subject of extensive debate. The anatomical vulnerability of these regions, including the absence of a sufficient perichondrial barrier at the anterior commissure, the presence of the cricothyroid gap, and the extensive lymphatic supply of the subglottis, often facilitates tumor invasion. [74] As a result, surgical management requires a highly individualized consideration. Extended vertical hemilaryngectomy offers a potential organ-preserving solution, but when tumor volume and structural compromise preclude its feasibility, total laryngectomy remains the definitive approach. In some cases, salvage or narrow-field completion total laryngectomy may become necessary due to complications such as airway obstruction, persistent dysphagia, aspiration, or postoperative fistula following failed transoral or open partial laryngectomy. [75,76]

Successful reconstruction in these cases requires addressing three primary challenges: the closure of extensive laryngeal and laryngotracheal defects, the restoration of laryngeal structural support, and the maintenance of a functional mucosal lining that minimizes cicatricial stenosis while providing sufficient airway clearance. An adequate airway must be secured in the glotto-subglottic space while simultaneously ensuring the stability of the supraglottic soft tissues, which may necessitate the replacement of cricoid and arytenoid cartilage. To maintain functional integrity, the posterior glottic area must be preserved to prevent aspiration, as it contains the highest density of sensory nerve endings supplied by the internal branch of the superior laryngeal nerve. The anteroposterior diameter of the airway should remain sufficient for optimal ventilation, and at least one mobile arytenoid cartilage must be retained to maintain sphincteric function. Resection margins must be planned meticulously, with the posterior midline respected and the structural stability of the arytenoid cartilage on the contralateral side ensured. [77]

The choice of reconstructive material plays a pivotal role in achieving optimal functional outcomes. The ideal graft should be structurally resilient to withstand fluctuations in airway pressure and potential external compression while also being malleable enough for shaping and suturing. Additionally, it must be readily available and epithelialized to promote mucosal healing. Tracheal cartilage is particularly suited for reconstruction, as its naturally curved C-cartilage structure provides mechanical support within the residual laryngeal framework. [78] Moreover, its relatively low metabolic activity ensures long-term durability, even following radiation therapy. [79] However, the vascularization of the airway mucosa poses a significant challenge. Isolated tracheal segments lack an independent microvascular network, which complicates revascularization. During rotational crico-thyrotracheopexy, segmental tracheoesophageal arteries must be sacrificed along the anterior segment, thereby leaving the proximal tracheal rings dependent on smaller tracheal artery branches for their blood supply. The risk of ischemia or anastomotic dehiscence is directly correlated with the degree of anastomotic tension and the extent of tracheal mobilization. [80,81]

Several surgical techniques have been developed to mitigate these risks to enhance tracheal and laryngeal mobility while reducing tension at the suture line. Various releasing maneuvers, including supramediastinal tracheal release by atraumatic dissection, infrahyoid and suprahyoid release, inferior pulmonary ligament lysis, pericardial dissection, and mediastinoscopy-assisted tracheal release, have been proposed to facilitate a tension-free anastomosis. [82] In this study, a combination of suprathyroid laryngeal release, superior mediastinal dissection, and the placement of heavy traction sutures on the prelaryngeal muscles was sufficient to achieve a secure and stable anastomosis. No cases of anastomotic dehiscence were observed. Although the reconstructed airway demonstrated immediate rigidity and structural stability, short-term stenting was employed to support mucosal healing and manage potential supraglottic edema. A Montgomery T-tube was preferred over conventional tracheostomy, as it allowed for airway humidification and minimized stomal trauma. [83]

The swallowing function remains a critical concern following laryngotracheal reconstruction, as certain surgical maneuvers may impair laryngeal elevation. Extended tracheal grafting, in particular, can exert a downward traction effect on the larynx, limiting its ability to elevate during swallowing. Additionally, the potential risk of recurrent laryngeal nerve injury on the preserved side may exacerbate aspiration. To optimize swallowing outcomes, the hyoid bone was preserved whenever possible, and resection margins were carefully planned to balance oncological safety with functional preservation. In this study, nasogastric feeding tubes were removed within three weeks postoperatively, and patient-reported MDADI scores indicated minimal dysphagia-related impairment. Preserving the epiglottis, aryepiglottic folds, and the posterior glottic area on the contralateral side contributed to restoring safe swallowing function. These structures serve as mechanical barriers and house the mechanoreceptors essential for proprioceptive feedback, which plays a crucial role in preventing aspiration. Additionally, neuroplasticity within the central nervous system enables partial compensation for unilateral vocal fold impairment, facilitating improved glottic closure during phonation. [84]

Subjective assessments indicated that patients generally perceived their voices as socially acceptable. Further refinements in voice rehabilitation, such as lipoaugmentation, may enhance phonatory outcomes. [85,86] While extended vertical hemilaryngectomy provides a viable alternative to total laryngectomy in selected cases, strict patient selection criteria must be adhered to in order to achieve favorable results. Contraindications include unresectable cervical lymph node metastases, an inability to reconstruct the esophageal inlet, severe pulmonary insufficiency, poor general health status, and cognitive impairment. Additionally, anatomical considerations, such as cervical spine hypomobility or a history of prior tracheal or mediastinal surgery, may reduce surgical feasibility and increase the risk of postoperative complications.

In summary, the management of advanced glottic-subglottic tumors necessitates a careful balance between oncological control and functional preservation. While total laryngectomy remains the gold standard for extensive disease, extended vertical hemilaryngectomy combined with innovative reconstructive techniques offers a promising alternative for carefully selected patients. Rotational crico-thyrotracheopexy presents several anatomical and functional advantages, including the maintenance of glottic sphincter function, adequate airway patency, and acceptable phonation outcomes. Ensuring adequate vascular supply, tension-free anastomosis, and structured postoperative rehabilitation remains essential for achieving long-term functional success. Based on our experience, meticulous patient selection, advanced reconstructive approaches, and targeted rehabilitation strategies can significantly enhance the quality of life for patients undergoing laryngotracheal reconstruction. Future advancements in biomechanical modeling, AI-assisted surgical planning, and refinements in reconstructive materials may further improve patient-specific customization and surgical predictability.

4.3 Integration of 3D Modeling in Reconstructive Laryngotracheal Surgery

The complexity of reconstructive laryngotracheal surgery necessitates precise preoperative planning, particularly in cases involving previous unsuccessful interventions or where conventional surgical techniques are associated with significant quality-of-life limitations. Following the example of other surgical specialties, including implantology and complex bone reconstruction, 3D surgical planning may become a routine practice in cases of complex laryngotracheal surgery. [18,19,55]

In tracheal and cardiac surgery, the application of 3D printing technology has already been incorporated for surgical simulation and procedural trials. Additionally, the use of 3D-printed models has been explored in the management of both adult and pediatric vocal cord paralysis, and in cases of maxillofacial deformities.[89,90,91,95] Despite the increasing prevalence of 3D preoperative planning in otolaryngology, particularly in temporomandibular and otologic surgery, its implementation in complex laryngeal resections remains relatively limited.[58] This limitation is primarily attributed to the intricate anatomical relationships within the pharyngeal-laryngeal region and the challenges posed by the narrow density spectrum of adjacent soft tissues in radiological imaging. Given these complexities, interdisciplinary collaboration among otolaryngologists, radiologists, and head and neck surgeons is critical to ensuring the accuracy and feasibility of 3D model development for surgical applications. [94]

Recent advances in machine learning-based segmentation techniques have further enhanced the potential for 3D modeling in airway surgery. AI-assisted segmentation methods have demonstrated promising results in automating model generation from imaging data, thereby reducing manual processing time and minimizing inter-operator variability. Future developments will likely integrate these AI-driven techniques to streamline the segmentation process and improve the precision of 3D reconstructions. Additionally, the incorporation of deep learning algorithms has shown significant potential in airway modeling, offering an avenue for further refinement in laryngotracheal surgical planning. [61,92]

Traditional silicone-based anatomical models have long been utilized for surgical training, allowing clinicians to practice procedural techniques and endoscopic maneuvers. While these models effectively replicate anatomical relationships, they lack the ability to reproduce patient-specific anatomical variations. Comparative studies have demonstrated the superior realism and customization potential of 3D-printed anatomical models, particularly in the training of complex surgical techniques. In dental education, for example, 3D-printed models of real teeth have been successfully used for technique practice, illustrating the broader applicability of patient-specific 3D modeling in medical training.[60] The objective of preoperative 3D planning is to generate models that accurately replicate the patient's laryngeal and tracheal anatomy, enabling the surgeon to perform a detailed preoperative assessment and optimize surgical planning. Beyond surgical training, 3D models of previously operated cases—available in both virtual and printed formats—offer valuable resources for educational courses and postgraduate medical instruction.

During the segmentation process, anatomical structures should be identified by comparing multiple imaging planes to ensure accuracy, particularly for intricate regions such as the vocal cords and supraglottic structures. The correlation of endoscopic findings with CT or MRI imaging data is essential to delineate endolaryngeal pathology precisely. As facilitated by ITK-SNAP software, real-time monitoring of the segmentation process enables iterative verification of the model's anatomical accuracy throughout its development.[96] Manual segmentation is time-consuming but is an efficient way to build precise virtual models of the laryngeal pathology.

Post-processing techniques play a crucial role in enhancing the uniformity of 3D-printed surfaces, correcting segmentation artifacts, and optimizing models for printing. Digital sculpting tools allow for refinements that improve anatomical fidelity, ensuring that fine structural details, such as cricoid cartilage contours and subglottic stenotic margins, are preserved. [88] These tools and software require advanced expertise in digital art and 3D-modelling. Collaboration with specialists significantly accelerates the process. Digital pens and capacitive displays have been shown to facilitate manual refinements with greater precision, offering a more efficient solution than using a mouse.

The transition from virtual modeling to 3D-printed surgical replicas highlights the vital role of material selection in creating clinically relevant models. While MEX printing was initially used as a feasibility test, it was found to lack the necessary flexibility and detail for effective surgical rehearsal. The insights gained from this phase informed subsequent refinements, leading to the adoption of VPP printing, which produced highly detailed, suturable, and resectable models. These results are consistent with prior studies in tracheal and cardiac surgery, where VPP models have shown significant advantages in surgical preparation. [94,95] Future research will concentrate on expanding patient cohorts, optimizing printing materials, and integrating AI-assisted segmentation techniques to further automate the workflow.

The selection of appropriate printing materials is fundamental to the clinical utility of 3D-printed models.[96] In this study, resin 80A material was selected for its capacity to maintain geometric stability while allowing for limited manual manipulation with surgical instruments and sutures. Cost considerations were also factored into the selection of printing materials and technologies to enhance feasibility for broader clinical implementation. The resulting printed models effectively demonstrated the key procedural steps of slide laryngotracheopexy and extended fronto-anterior partial laryngectomy. Additionally, digital models allowed for interactive manipulation within a virtual environment, further supporting surgical training and procedural planning.

In addition, 3D modeling serves as an effective tool for patient education. Given the complexity of reconstructive laryngotracheal surgery and the need for patients to have a clear understanding of their treatment options, visual aids such as 3D models can significantly enhance doctor-patient communication. The ability for patients to examine digital or printed models of their airway structures allows for improved comprehension of the surgery and expected outcomes. Comparing preoperative and postoperative anatomical models enables patients to visualize the changes in their anatomy, thereby fostering greater confidence and engagement in their treatment. The integration of 3D modeling into patient education is expected to have long-term benefits, promoting informed decision-making and enhancing the overall patient experience.

5. Limitations and Future Directions

The clinical studies are limited by a small sample size, retrospective design, and single-center experience. The rarity of idiopathic subglottic stenosis (iSGS) inherently restricts patient recruitment, and extended partial laryngectomy with rotational thyrotracheopexy is only feasible in selective cases. To validate the long-term outcomes of these novel laryngotracheal surgeries, multicenter prospective studies are required. Comparative research with conventional and extended cricotracheal resection (CTR) and chemoradiotherapy is also necessary to better define the role of these techniques. Segmentation remains a time-intensive process, though AI-driven automation may improve efficiency.

6. Conclusion

Idiopathic subglottic stenosis remains a challenging condition requiring surgical intervention due to its progressive fibroinflammatory nature. Slide laryngotracheopexy has emerged as a promising one-step open-neck procedure that utilizes a local tracheal flap to bypass the stenotic segment while preserving the structural integrity of the cricoid. This approach ensures stable airway function, maintains phonation and swallowing, and demonstrates a lower restenosis rate compared to conventional cricotracheal resection. Long-term outcomes indicate its potential as a superior alternative, necessitating further comparative studies with larger patient cohorts to validate its efficacy.

In the management of advanced laryngeal malignancies requiring extended vertical hemilaryngectomy, rotational crico-thyrotracheopexy offers a viable function-preserving alternative to total laryngectomy. Utilizing well-vascularized, locally available tracheal tissue enables reconstruction of the laryngeal framework while maintaining adequate airway patency, socially acceptable voice quality, and safe swallowing. The study confirms its feasibility in selected cases, providing oncological reliability without compromising key laryngeal functions.

Advancements in CT-based 3D modeling and printing have introduced a high-fidelity approach to preoperative planning, surgical training, and visualization in complex laryngotracheal procedures. These patient-specific models offer anatomically precise representations, enhancing surgical decision-making and medical education. Future research will focus on refining materials, expanding patient studies, and integrating AI-assisted segmentation to improve accuracy and streamline workflow, further solidifying the role of 3D technology in modern surgical practice.

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