Case Report

Robot-Assisted Correction of a Supra-Long Tracheal Stenosis Using C-Type Nickel–Titanium Alloy Exterior Stenting and Suspension Fixation Technique: A Case Report

Jingquan Han,[1] Xi Yan,[1] Hongwei Cui,[2] Hang Zhang,[1] Bei Lu,[1] and Jinzhi Xu[1]

T-tubes and airway stents are commonly used but have limited effectiveness and frequent complications. A 50-year-old male patient presented with severe tracheal stenosis, affecting an 8.7 cm length of the airway. We employed an innovative approach known as external suspension fixation of tracheal stent using robotic assistance. This method involves surgically attaching the stent to the exterior of the trachea to provide support and stabilize the softened or collapsed tracheal segments. We designed a C-shaped nickel–titanium alloy exterior stent and successfully fixed it using robotic assistance. This intervention effectively restored tracheal function and led to a favorable postoperative recovery. The technique does not affect tracheal membrane function or airway mucociliary clearance. It could potentially be considered as a new option for treating long-segment benign tracheal softening or collapse.

Keywords: tracheal stenosis, extra-tracheal stent, C-shaped nickel–titanium alloy, robotic-assisted surgery, case report

Introduction

Endotracheal tuberculosis and tracheal intubation are the principal causes of benign tracheal stenosis.[1)] Depending on the location and severity of the lesion, tracheal stenosis can manifest in different symptoms such as shortness of breath, cough, sputum production, wheezing, and frequent respiratory infections. The condition can be lethal if left untreated, leading to suffocation-induced death. Among several available treatment options for tracheal stenosis, surgical resection and reconstruction stand are the most preferred measures. Over the previous six decades, therapeutic progress in tracheal surgery has brought about positive outcomes in tracheal lesion resection and reconstruction. However, the extent of tracheal removal is constrained. If a large part of the trachea (more than 50% or 6 cm in adults or 30% in children) is excised, end-to-end anastomosis might not be successful due to the excessive tension at the anastomosis site, necessitating tracheal replacement.[2)] A few tracheal substitutions have shown potential results in animal studies and preliminary clinical applications, but none have achieved widespread clinical implementation due to high complication and mortality rates.[3)] Long-term placement of T-tubes or airway stents is a surgical treatment option to alleviate symptoms in adults with long non-neoplastic lesions that cannot be surgically removed and reconstructed.

[1]*Department of Thoracic Surgery, the Fourth Affiliated Hospital of Harbin Medical University, Harbin, China*
[2]*The Eighth Ward of Tuberculosis, Harbin Chest Hospital, Harbin, China*

Received: January 17, 2024; Accepted: April 25, 2024
Corresponding author: Jinzhi Xu. Department of Thoracic Surgery, the Fourth Affiliated Hospital of Harbin Medical University, Yiyuan Street 37, Nangang District, Harbin 150001, Heilongjiang, China
Email: 13836027105@139.com

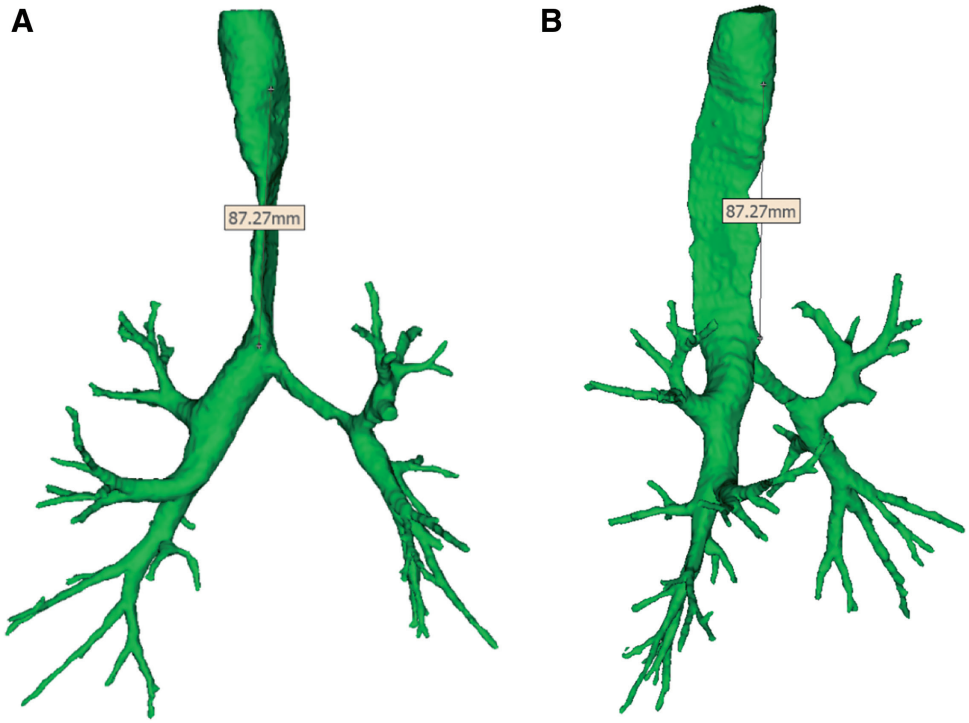

Fig. 1 Three-dimensional reconstruction of the trachea. (**A**) Coronal view and (**B**) sagittal view.

However, this treatment option has potential complications, including stent migration and the growth of granulation tissue, which may result in recurrent stenosis of the benign airways. Therefore, it is not deemed an optimal treatment option.[4)]

Extra-tracheal stent fixation is a surgical procedure in which a stent is sutured to the outside of the trachea to strengthen a weakened or collapsed trachea. This method assists in sustaining the mucosal ciliary structure of the airway, hence reducing the risk of complications such as airway blockage. In contrast to trachea airway stenting, this technique is commonly used in pediatric cases.[5)] This case report presents an innovative treatment for a male adult with severe tracheal stenosis (8.7 cm in length), using a custom-designed C-shaped airway exterior stent made of nickel–titanium memory alloy. The stent is securely fixed to the cartilaginous side of the airway through minimally invasive robotic-assisted surgery, aiming to restore normal tracheal function.

Case Presentation

Patient characteristics

A 50-year-old male patient with a height of 165 cm and a body mass index of 29 was diagnosed with tracheal stenosis caused by endotracheal tuberculosis ten years ago. An airway stent was placed for a short period but had to be removed due to granuloma occlusion. After that, he received conventional anti-tuberculosis treatment with isoniazid, rifampicin, and pyrazinamide. Despite experiencing shortness of breath following physical activities over the past decade, he was still capable of performing daily activities and working. However, in the last six months, the patient had recurrent lung infections with sputum obstruction, which led to a life-threatening emergency requiring hospitalization. Three-dimensional reconstruction imaging revealed significant stenosis and deformation of the left trachea (**Fig. 1**) without any significant scarring. The stenosis measured 8.7 cm with a total tracheal length of 11 cm. Tracheal mucosal biopsy was negative for *Mycobacterium tuberculosis*.

Production of tracheal stent

The extra-tracheal stent (Jiangsu Brightness Medical Devices Co., Ltd., Jiangsu, China) is made of Nitinol wire, which can be customized according to the patient's actual needs. We use Nitinol wire with a diameter of 0.26 mm, woven into a rectangle with a width of 1 cm, and each mesh hole with a diameter of 1.8 mm × 1.8 mm, and then shaped into a "C" structure with an opening ring of 240°. For this male patient, we designed and customized the outer bracket with a diameter of 2.6 cm (**Fig. 2**).

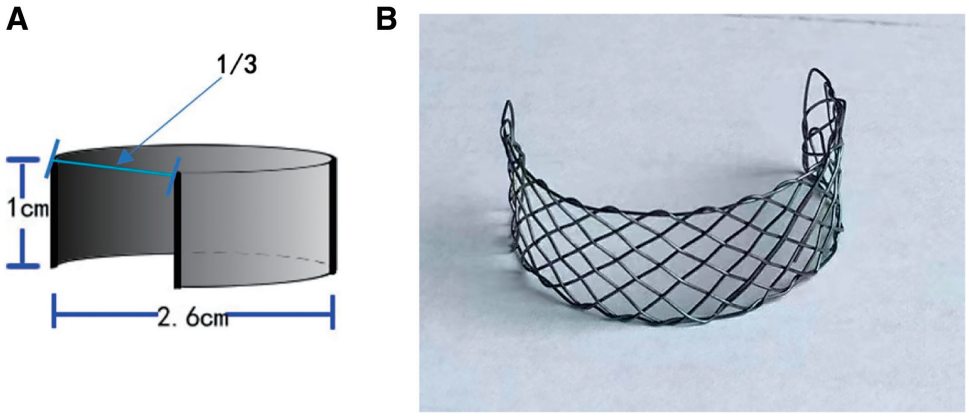

Fig. 2 The customized outer bracket. (**A**) Schematic diagram of the outer bracket, (**B**) product diagram of the outer bracket.

Robotic-assisted surgery

Tracheal 3D and bronchoscopy were used to assess the tracheal narrowing before the operation. The patient's airway was completely narrowed from the second cartilage to the carina, where the length of the tracheal stenosis was 8.7 cm. This stenosis was particularly pronounced during expiration, making it almost impossible for the bronchoscope to pass through. Following a full assessment by a specialist team, it was decided that a robot-assisted minimally invasive procedure would be carried out to place a stent on the outside of the trachea. The patient was positioned supine for the procedure. After single-lung endotracheal intubation, the right side was elevated at a 30° angle. The robotic lens arm was placed at the seventh intercostal space of the midclavicular line, while the No.2 arm was at the anterior axillary line at the fifth intercostal space, connected to a bipolar electrocoagulation forceps. The No.1 arm is placed in the subxiphoid incision and connected to the electrocoagulation hook (**Fig. 3A**). Meanwhile, an artificial pneumothorax of 8–10 mmHg was created. Following this, a 3–4 cm longitudinal incision was made in the skin beneath the xiphoid process. The subcutaneous fascia and muscle layer were separated to expose the xiphoid process cartilage, which was subsequently removed.[6] Subsequently, a tunnel was created behind the costal arch. The mediastinal pleura was opened, and an incision protector was inserted under camera monitoring. Auxiliary equipment was inserted into the chest through the No. 2 arm to assist in pulling the superior vena cava and using a suction device to suck the chest. Within the quadrilateral area bordered by the inner edge of the superior vena cava, the inner edge of the ascending aorta, the lower edge of the brachiocephalic trunk artery, and the right pulmonary artery perform a complete dissection of the front surface of the trachea. This dissection was extended from the second cartilage ring to the carina, fully exposing the tracheal cartilage while preserving the blood supply to the membranous side. A self-designed C-shaped nickel–titanium memory alloy-coated tracheal exterior stent was inserted. Nonabsorbable sutures (5–6 needles) are used to penetrate the tracheal cartilage and firmly fix the external fixation stent on the tracheal cartilage side. Additionally, a Dacron cardiac repair material was utilized to completely separate the trachea from the surrounding blood vessels (**Figs. 3B–3D**, and **Video 1**; the video is available online). During the dissociation of the second and third cartilaginous rings, the anesthetist was advised to tilt the patient's head forward to descend the trachea into the chest cavity. The extra-tracheal stent was placed from the cephalic side of the trachea. At this point, the balloon of the endotracheal tube was positioned above the carina. After placing the stent above the carina, the anesthesiologist moved the endotracheal tube up to below the glottis to avoid puncturing the endotracheal tube balloon with the suture needle.

The operation lasted for five hours. Ultimately, three exterior stents, each 1cm in width and 2.6 cm in diameter, were firmly attached to the tracheal cartilage. These stents were positioned at intervals of 1 cm (the distance between two cartilage rings) to correct the tracheal deformity. The results of bronchoscopy before, during, and 2 weeks after the operation are presented in **Figs. 4A–4C**. The trachea was completely dilated, and the normal tracheal structure was essentially restored.

Follow-up and outcomes

After the surgery, the patient was transferred to the intensive care unit and received assisted mechanical ventilation for 12 hours. The patient's breathing was closely

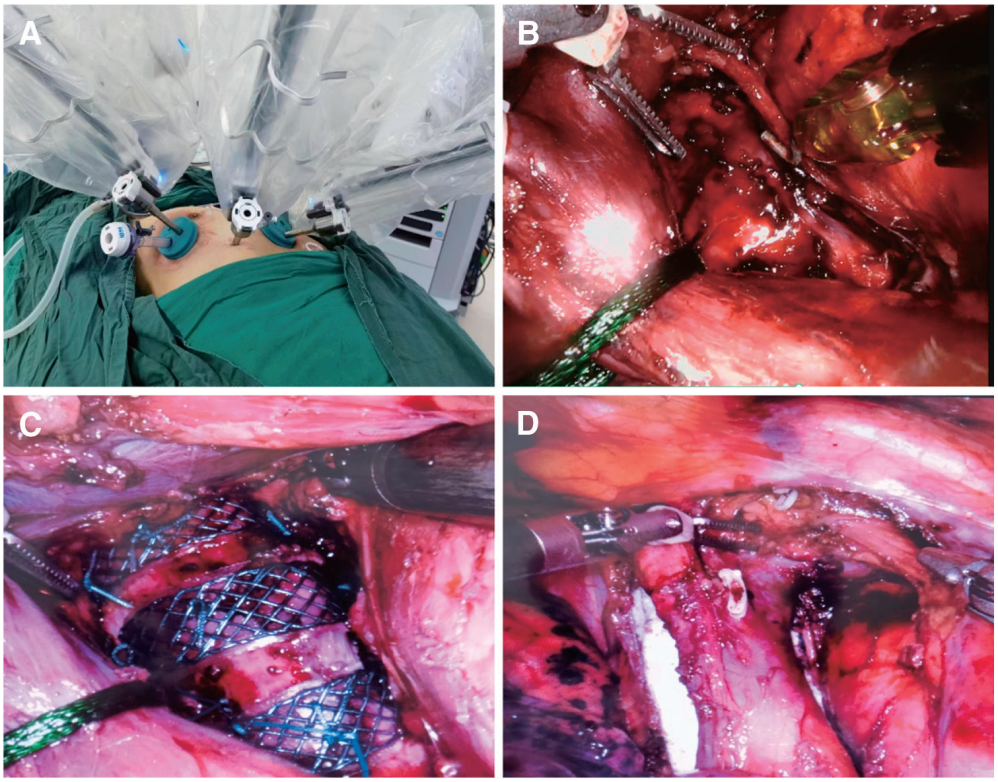

Fig. 3 Extra-tracheal stent suspension and fixation surgery. (**A**) Placement of robot arms, (**B**) dissection of the tracheal cartilage side of the trachea between the superior vena cava, the innominate vein, and the aortic arch, (**C**) suspension of the nickel–titanium alloy memory metal extra-tracheal stent on the deformed cartilage side of the stenotic trachea, and (**D**) the use of Dacron cardiac repair material to create complete separation between the trachea and surrounding blood vessels.

monitored, and once the patient resumed spontaneous breathing, the tube was removed. The patient experienced significant relief from dyspnea after the operation. The patient was determined to be stable enough to be transferred to the thoracic surgery ward on the second day. The patient successfully recovered and was discharged two weeks after the operation. The patient's breathing and physical strength showed remarkable improvement during the six-month follow-up period, enabling them to resume his normal daily activities comfortably. Chest computed tomography was taken 6 months after the surgery (**Figs. 4D** and **4E**). The results showed that the stent placed in the mediastinum remained stable without any complications or adverse reactions.

Discussion

The trachea plays a crucial role in the human body, fulfilling two vital functions. Firstly, it serves as a gas-tight and mechanically stable conduit, linking the throat and bronchi. This is achieved through its cylindrical design, supported by anterior cartilage rings and longitudinal muscles. This structure offers both lateral rigidity and longitudinal flexibility, guaranteeing that the airway remains open and stable. Secondly, in addition to its structural role, the trachea also assists in removing secretions from the respiratory tract. Specialized epithelial cells with synchronized cilia work together to move the secretions upward toward the mucociliary escalator. From there, the secretions are expelled from the airway, contributing to maintaining a clean and healthy respiratory tract.[7,8] Various pathologies, such as tuberculous infections, as well as congenital and mediastinal lesions, can inhibit the blood and nutrient supply to the cartilage that supports the trachea, weakening its wall and causing deformity, leading to compromised function.[9,10] Tracheal resection and reconstruction are common surgical treatments in clinical settings, but there are limitations on the length of the trachea that can be removed. When the diseased portion of the trachea exceeds its tolerable limit, the implantation of substitutes for the trachea becomes necessary to restore tracheal continuity and maintain an open airway. Currently, all existing airway substitutes are unable to replicate the secretion removal function of

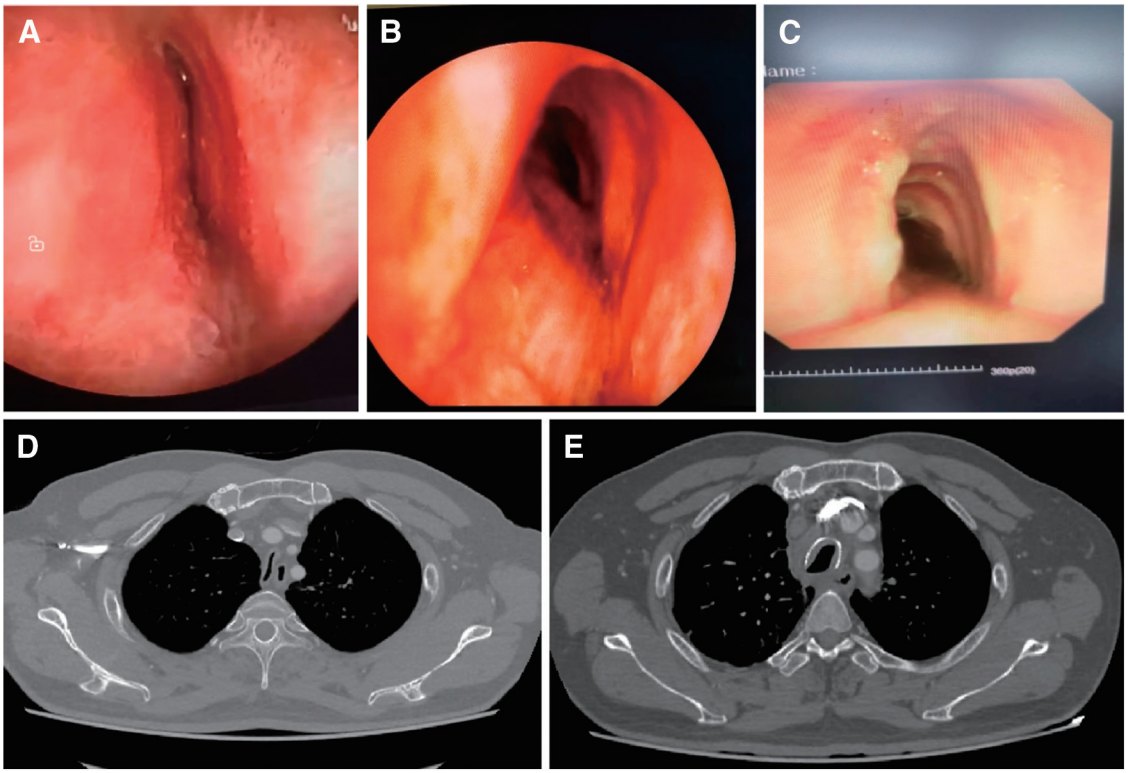

Fig. 4 Bronchoscopic and CT images before and after surgery. (**A**) Preoperative bronchoscopic image of the trachea, (**B**) intraoperative bronchoscopic image of the trachea, (**C**) bronchoscopic image 2 weeks after surgery, (**D**) preoperative chest CT image, and (**E**) 6 months postoperative chest CT image. CT, computed tomography

the native trachea. Although autologous tissue trachea has promising potential due to the absence of donor limitations and the avoidance of immunosuppressants, it lacks the ability to clear secretions through tracheal cilia. Therefore, in the short-term postoperative period, patients still face problems related to stent implantation and frequent removal of airway secretions.[3)]

Longer non-neoplastic lesions that cannot be safely resected can usually be treated with a T-tube or airway stent for extended periods, but they require regular cleaning of sputum crusts and management of granuloma issues.[11)] A meta-analysis of airway stent for the treatment of nonmalignant tracheal narrowing found that complications occurred in approximately 20% of cases.[12)] These complications included stent migration (25.04%), the development of granulation tissue (15.66%), and mucus accumulation (23.82%). Half of the patients who needed stent removal underwent routine extraction, while the rest commonly experienced excessive growth of granulation tissue, typically observed around 89.9 days after stent insertion.[13)] The most common complication among patients undergoing stent removal was recurring fistula or stenosis requiring re-stenting. Within one year, the restenosis rate was 58%, with 85% of participants experiencing this condition within a month.[14)] This condition was particularly prevalent in patients with diabetes, morbid obesity, and frequent complications associated with stent usage.

Extra-tracheal stenting is a surgical fixation of the stent outside the trachea to support the softened or collapsed deformed trachea. This technique has several potential advantages over other methods, such as avoiding the formation of sputum crusts and granulomas. Additionally, the use of a C-shaped stent does not impact the tracheal membrane or disrupt the structure of the airway's mucosal cilia. This type of stenting helps to restore the function of the tracheal membrane, making it easier for sputum to be cleared. As a result, extra-tracheal stenting may represent a more effective treatment option for benign tracheal softening or collapse. Despite the collapsed tracheal segment being heavily adhered to the surrounding tissue, the use of robotic technology allowed us to completely free the front surface of the trachea while preserving the blood supply to the membranous part. We used a C-shaped extra-tracheal stent with a 240° opening loop, which did not compromise

the tracheal support effect and facilitate suturing and fixation during minimally invasive robotic procedures. Following the operation, the patient experienced evident congestion and edema in the tracheal mucosa but fully recovered within 2 weeks, returning to a normal state.

There are various biomaterials available that can serve as support structures to fix or stabilize segments of the anterior cartilage or posterior membrane. These biomaterials include meshes, sternal plates, and bioabsorbable materials.[15,16] However, currently, there is a lack of specialized models for these structures. Surgeons have to create them intraoperatively according to the specific requirements of each case. In light of this, it becomes crucial to develop an extra-tracheal stent that is commercially available and can be personalized. This stent should possess a design that suits individual needs, exhibits good biocompatibility, and has sufficient mechanical strength. The memory metal known as nickel–titanium alloy has shown exceptional compatibility with tissues, eliminating the need for additional surgeries for its removal. It is intermittently suspended on the outer wall of the trachea without affecting its lateral hardness and longitudinal softness characteristics. Previously used inside the trachea, this material has now been adapted into a C-shaped exterior stent that can be fixed to the lateral side of tracheal cartilage, effectively restoring the functionality of the original airway.

Until a perfect airway substitute is discovered, research on extra-tracheal stents holds great promise for patients suffering from long-segment benign tracheal collapse or softening. Making significant advancements in tracheal surgery beyond its current limitations is a challenging task. However, any bold endeavor in this constrained field indicates that the boundaries of this field are continuously being pushed. The application of robotic minimally invasive technology to release the front surface of the trachea showcases the distinct advantages of robotic surgery in this confined area. Specifically, it eliminates the need for median sternotomy, reducing associated trauma, and achieves surgical outcomes that surpass even those attainable through median sternotomy.

Conclusion

This case report presents an innovative treatment approach for a male adult with severe tracheal stenosis. The patient was treated using a custom-designed C-shaped extra-tracheal stent made of nickel–titanium memory alloy using minimally invasive robot-assisted surgery. After the operation, the patient experienced a significant improvement in symptoms without any complications.

Declarations

Funding

None.

Ethical statement

The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The technique described in this manuscript has been approved by the Ethics Committee of the Fourth Affiliated Hospital of Harbin Medical University (Approval Number: 2023-Ethics Review-45-44). All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee(s) and with the Declaration of Helsinki (as revised in 2013). Written informed consent was obtained from the patient for publication of this case report and accompanying images.

Data availability statement

All available data were included in this published case report.

Author contributions

Conception and design: JX and JH
Administrative support: XY and HZ
Provision of study materials or patients: XY and HZ
Collection and assembly of data: HC and BL
Data analysis and interpretation: HC and BL
Manuscript writing: All authors
Final approval of manuscript: All authors.

Disclosure statement

The authors declare that they have no competing interests.

Supplementary Material

Video 1 Surgical procedure.

References

1) Fang Y, You X, Sha W, et al. Bronchoscopic balloon dilatation for tuberculosis-associated tracheal stenosis: a two case report and a literature review. J Cardiothorac Surg 2016; **11**: 21.
2) Grillo HC. Tracheal replacement: a critical review. Ann Thorac Surg 2002; **73**: 1995–2004.
3) Fabre D, Kolb F, Fadel E, et al. Successful tracheal replacement in humans using autologous tissues: an 8-year experience. Ann Thorac Surg 2013; **96**: 1146–55.
4) Wood DE, Liu YH, Vallieres E, et al. Airway stenting for malignant and benign tracheobronchial stenosis. Ann Thorac Surg 2003; **76**: 167–72, discussion 173–4.
5) Zopf DA, Flanagan CL, Wheeler M, et al. Treatment of severe porcine tracheomalacia with a 3-dimensionally printed, bioresorbable, external airway splint. JAMA Otolaryngol Head Neck Surg 2014; **140**: 66–71.
6) Han J, Zhang H, Ma X, et al. Robot-assisted resection of multiple lung nodules through combination of intercostal incisions and a subxiphoid incision as a utility port. Int J Med Robot 2023; **19**: e2507.
7) Belsey R. Resection and reconstruction of the intrathoracic trachea. Br J Surg 1950; **38**: 200–5.
8) Hamilton N, Bullock AJ, Macneil S, et al. Tissue engineering airway mucosa: a systematic review. Laryngoscope 2014; **124**: 961–8.
9) Murgu SD, Colt HG. Tracheobronchomalacia and excessive dynamic airway collapse. Respirology 2006; **11**: 388–406.
10) Carden KA, Boiselle PM, Waltz DA, et al. Tracheomalacia and tracheobronchomalacia in children and adults: an in-depth review. Chest 2005; **127**: 984–1005.
11) Chin CS, Litle V, Yun J, et al. Airway stents. Ann Thorac Surg 2008; **85**: S792–6.
12) Chen DF, Chen Y, Zhong CH, et al. Long-term efficacy and safety of the Dumon stent for benign tracheal stenosis: a meta-analysis. J Thorac Dis 2021; **13**: 82–91.
13) Bi Y, Li J, Bai L, et al. Long-term outcomes of tracheal stents removal under fluoroscopy guidance: comparison of tracheal fistulas and tracheal stenosis. BMC Pulm Med 2021; **21**: 14.
14) Chrissian AA, Diaz-Mendoza J, Simoff MJ. Restenosis following bronchoscopic airway stenting for complex tracheal stenosis. J Bronchology Interv Pulmonol 2023; **30**: 268–76.
15) Liu Z, Yang R, Shao F, et al. Controlled trachea suspension for tracheomalacia after resection of large anterior mediastinal mass. Ann Thorac Surg 2015; **99**: 2225–7.
16) Huang L, Wang L, He J, et al. Tracheal suspension by using 3-dimensional printed personalized scaffold in a patient with tracheomalacia. J Thorac Dis 2016; **8**: 3323–8.