A modified procedure of T-tube maneuver to treat tracheal total obstruction involving ablative bronchoscopy sparing open surgical intervention

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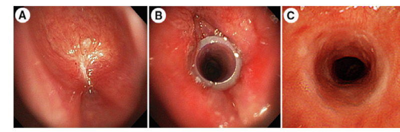
ABSTRACT

Objectives: The study objectives were to test an innovative T-tube procedure involving ablative bronchoscopy for the treatment of total airway occlusion and to orchestrate a safe and nontraumatic maneuver to treat intricate subglottic stenosis amenable for substituting the conventional surgical intervention.

Methods: This was an uncontrolled single-center cohort study on 1254 patients from January 2001 to June 2021. Patients underwent the modified T-tube procedure treatment for tracheal stenosis. Only 42 patients were included in the study because they had full records for subglottic total occlusion sitting tracheostomy. The ablative bronchoscopy, aided by a fixed suspending laryngoscope, was applied to retunnel their total airway occlusion. T-tube revision and removal were conducted under general anesthesia with laryngeal mask airway aid during follow-up.

Results: The primary outcome was 90-day mortality. The secondary outcome was 90-day morbidity. The 42 patients included in the study had a mean age of 52.29 years (range, 9-84 years) with 22 men (52.38%). Their mean length of hospital stay was 13.67 days (range, 2-45 days). Their mean operation time was 73 minutes (range, 43-256 minutes). Their mean length of the tracheal stenosis was 2.8 cm (range, 0.8-6.3 cm). Outcomes were good in 29 patients (69.05%), satisfactory in 10 patients (23.81%), and considered failures in 3 patients (7.14%). A total of 16 patients (38.10%) underwent decannulation, and 3 patients (7.14%) were shifted to a Shiley tracheostomy. All 42 patients had a median follow-up of 6.2 years (range, 1.5-16.3 years).

Conclusions: The modified T-tube procedure, which offered both resilience and versatility, improved the conventional technique in treating those patients experiencing total tracheal stenosis and who were unqualified for conventional open surgery. (JTCVS Techniques 2023;22:317-30)



Intricate subglottic stenosis with a fully obstructed lumen before and after treatment.

CENTRAL MESSAGE

A modified T-tube procedure is an optimal alternative for the first-line treatment of tracheal stenosis that is not amenable to conventional surgical intervention.

PERSPECTIVE

The novel T-tube procedure for the treatment of tracheal stenosis with an existing tracheostomy tube that is contraindicated for open surgical intervention can be proposed as the first line of surgical treatment.

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Video clip is available online.

The raging COVID-19 pandemic devastated the world's health system.[1] During that time, long-term intubation and high rates of tracheostomy for patients with COVID-19 may have led to an unprecedented increase in airway stenosis.[2] The introduction of percutaneous dilatational tracheostomy into common clinical use generated new patterns of associated airway problems. Although the use of percutaneous dilatational tracheostomy does not affect rates of stenosis, it has shifted the stenotic location closer to the narrowest subglottic space. Consequently, the treatment becomes more challenging.[3]

Intricate subglottic stenosis complicated by a total occlusion is rare. It is hard to determine the true cause of total

Abbreviations and Acronyms
LMA = laryngeal mask airway
S/P = status of postoperation

tracheal stenosis, especially when it is located over the subglottic or upper trachea sitting a tracheostomy tube. Subglottic stenosis is classified on the basis of its length, diameter (Figure E1), and consistency.[4] Previous treatments for secondary benign airway stenosis are mostly based on curative surgical resection and reconstruction.[5] Surgical management for subglottic stenosis through the use of laryngotracheoplasty and cricotracheal resection provides a definitive form of treatment.[6] In addition, surgical treatment requires patients to be in good condition and to be able to tolerate the surgery.[7] Surgical alternatives are typically pursued in the absence of inadvisable resection due to contraindication from local and systemic factors. The use of interventional bronchoscopic treatments has greatly increased in recent years. They include lasers, mechanical dilation, and stenting. However, their application for subglottic stenosis remains limited because of the challenging anatomic and technical issues.[8] The dilemma is that only T-tubes that are able to pass through the vocal cords are well tolerated for the treatment of subglottic stenosis, as reported by Cooper and colleagues.[9] A number of T-tube insertion techniques have been used with satisfactory outcomes.[10-15] The T-tube has the advantage of being adaptable to the individual characteristics of patients. Its arms can be modified for an exact fit, and T-tubes are available in various lengths and diameters.[16] Conventional T-tube insertion for intricate subglottic stenosis with difficult upper-arm fitting is hampered when performed under the guidance of a rigid bronchoscope. Such a bronchoscope is not suitable in conditions involving prognathous jaws, severely fixed cervical deformity, temporomandibular joint fixation after a stroke, or limited mouth opening capability due to previous oral surgery.[17]

In cases that involve various underlying pathologies, fitting a T-tube is likely difficult particularly when seating the upper end of the tube. The current manipulation is both frenetic and time-consuming. Thus, most experienced surgeons are discouraged to adopt such a procedure. We have designed an innovative T-tube insertion procedure that is both safe and sharp to securely snap the tube to a fitting position. The primary outcome was 90-day mortality. The secondary outcome was 90-day morbidity. Given a 20-year validation of this modified T-tube treatment, we hypothesized that it is a convincing candidate procedure to treat total airway obstruction.

PATIENTS AND METHODS

Patients

From January 2001 to November 2022, a total of 1254 patients underwent a modified T-tube procedure treatment for tracheal stenosis. Only 42 patients experienced the most severe stenosis and had accountable records for our study. We collected their clinical data (including clinical features, efficacy, complications, and prognosis) and retrospectively analyzed them with the aim to evaluate this innovative technique in secondary benign airway stenosis after tracheostomy. Patients with a complete airway obstruction were excluded from the study if they had any one of the following conditions: (1) unable to give consent or not affiliated with the Taiwan Social Security System; (2) having a nonresectable major locally invasive tumor or an untreatable metastatic tumor; (3) experiencing obstructions manifested by thick calcification not amenable to laser ablation; (4) having mental confusion and failure to follow orders; and (5) diagnosed with a recent myocardial infarction. Our study was approved by the Institutional Review Board of Taichung Veterans General Hospital (TCVGH-CG23172A, approved July 28, 2023). Each patient provided written informed consent to participate in the study for the publication of their study data including pictures and videos.

Study Design

Preoperative evaluation. Apart from a routine examination, all patients received computed tomography imaging. Computed tomography assisted in treatment planning by identifying the extent of the tracheobronchial stenosis, extraluminal component of the lesions, and patency of the distal airways. It allowed the evaluation of length of laryngotracheal stenosis in cases of complete (grade IV) airway obstruction, as well as a deeper insight into the altered laryngotracheal framework due to its deformity, fracture, or collapse.[18]

T-tube preparation and modification. Characteristics of the commercial T-tube and its placement features were as follows: (1) outer diameter ranged from 6 to 16 mm; (2) provided in pediatric, standard, long, and extra-long lengths (up to 15 cm); and (3) tubes were trimmed to the precise size fitting the individual patient determined during operative bronchoscopy (Video 1). T-tubes were modified at 1 or both ends to achieve the precise fit. A commercial T-tube was tailored for the shape, length, and width to fit the underlying airway (Figure E2).

Surgical Procedure

Suspended fixed-laryngoscopic assistance. Step 1: Assess the upper airway. To begin, a laryngoscope (Figure 1, *A*) was inserted to elevate the epiglottis for visualizing the glottis. A flexible video

VIDEO 1. T-tube modification. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00302-4/fulltext.

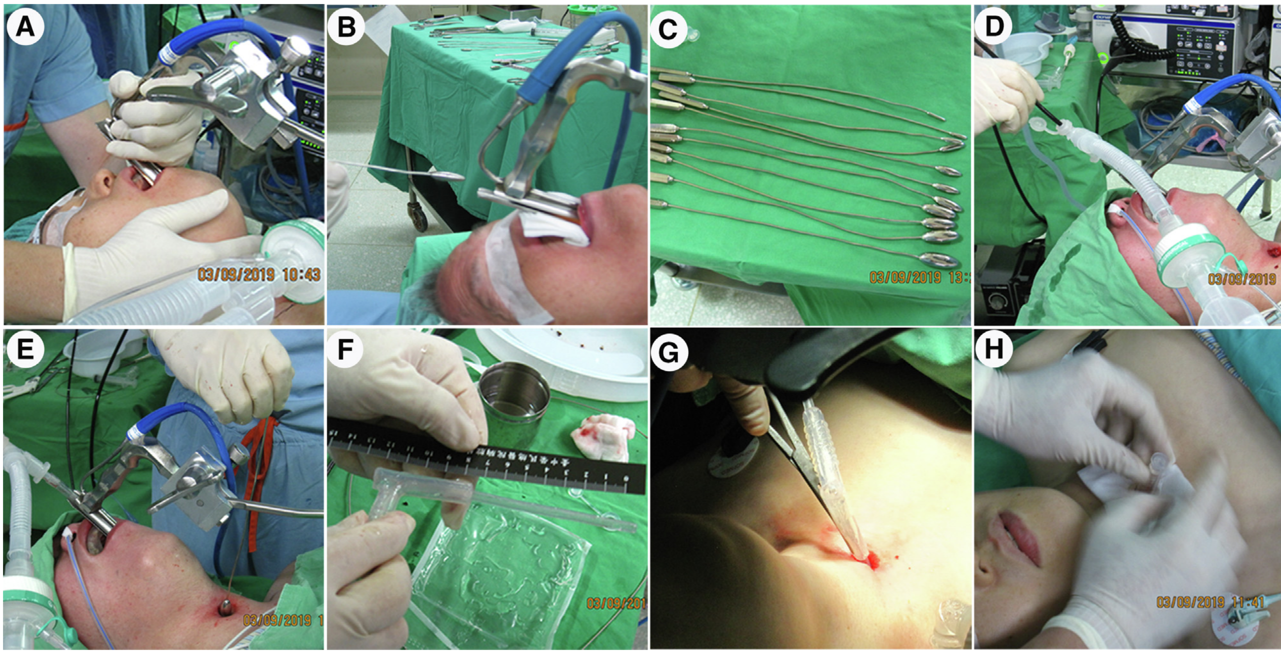
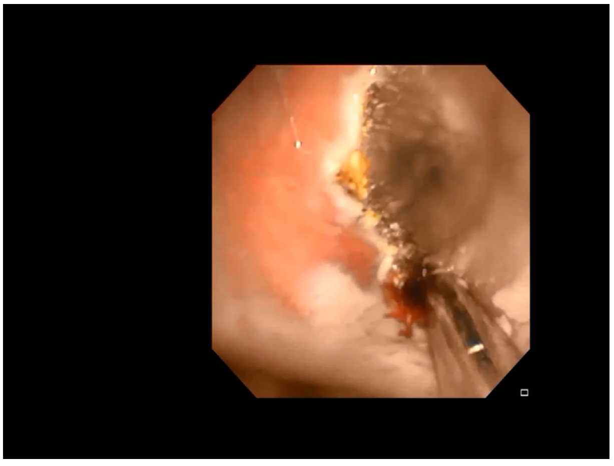


FIGURE 1. Maneuvers of T-tube insertion during an ordinary procedure. A, To begin, the laryngoscope was applied to elevate the epiglottis to visualize the glottis. A video flexible bronchoscopy was then used to explore the lesion. Laser excision (Nd-YAG or Argon plasma) of the stricture was performed. B and C, Baker dilator or rigid bronchoscopy with a variable caliber was used for serial dilations. D, Under bronchoscopic guidance, a flexible endotracheal tube was used for dilation and ventilation (at a 7- or 8-mm diameter) after removal of the tracheostomy tube. E, Stomaplasty was performed to remove surplus granulation or lysis of peristomal fibrosis with cautery, followed by dilation using the fingers or a Baker dilator around the small leading wound. Likewise, the revision of obliquity of the tracheostomy tract to a right angle was applied with cautery or instruments. F, Accurate measurements of the length of the lesion and its relevant distance from the stoma were used to determine the optimal option of the T-tube. G and H, In an uncomplicated situation after thorough dilation, we applied a 14F sputum suction tube that traveled from the side arm to the distal end of the T-tube (∼10 cm beyond the edge). Upon full lubrication of the inside and outside of the tube, a Kelly clamp was used to secure the lower arm of the T-tube, which was pushed in combination with an upward traction to reach the distal trachea, until its submergence and snapping of the tube occurred automatically.

bronchoscope was applied to identify the lesion. Step 2: Recanalization of atresia. A laser excision (Nd-YAG or Argon plasma) was performed first, followed by the use of a Baker dilator on the stricture (Figure 1, *B*). Alternatively, a rigid bronchoscope with a variable caliber (Figure 1, *C*) was applied for serial dilations. Step 3: Create a patent airway. Serial dilations continue until an adult-sized (Figure 1, *D*) bronchoscope was able to pass through. In the case of long segments experiencing stenosis, we analyzed the anatomic structure through retrograde explorations, starting from the distal end of the atresia trachea. A laser was used at the proximal end of the trachea for the recanalization of airway atresia (Video 2). Under bronchoscopic guidance, a flexible endotracheal tube (of 7-8 mm diameter) was applied for both dilation and ventilation after the removal of the tracheostomy tube. Step 4: Pursue a perfect stoma. A stomaplasty was performed using cautery to remove surplus granulation or lysis of the peristomal fibrosis, followed by dilation with fingers or a Baker dilator around the small leading wound (Figure 1, *E*). Likewise, revision of deviation of the tracheostomy tract to a right angle was applied with cautery or instruments. Step 5: Select the appropriate T-tube size. Accurate measurements of both length of the lesion and its relevant distance from the stoma under operative bronchoscopy were used to determine the optimal size of T-tube (Figure 1, *F*).[17]

(1) T-tube lip of upper-arm easy sitting using a 14F suction tube to guide the lower arm of the T-tube for insertion:

Step 6: Routine insertion of the common T-tube. In an uncomplicated setting after thorough dilation, we applied a 14F sputum suction tube that traveled from the side-arm to the distal end of the T-tube (∼10 cm beyond the edge). This procedure was performed to prevent the formation of a false lumen due to unnecessary trauma, because this happened in certain difficult situations (such as those involving deep neck trachea,



VIDEO 2. Airway atresia recanalization. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00302-4/fulltext.

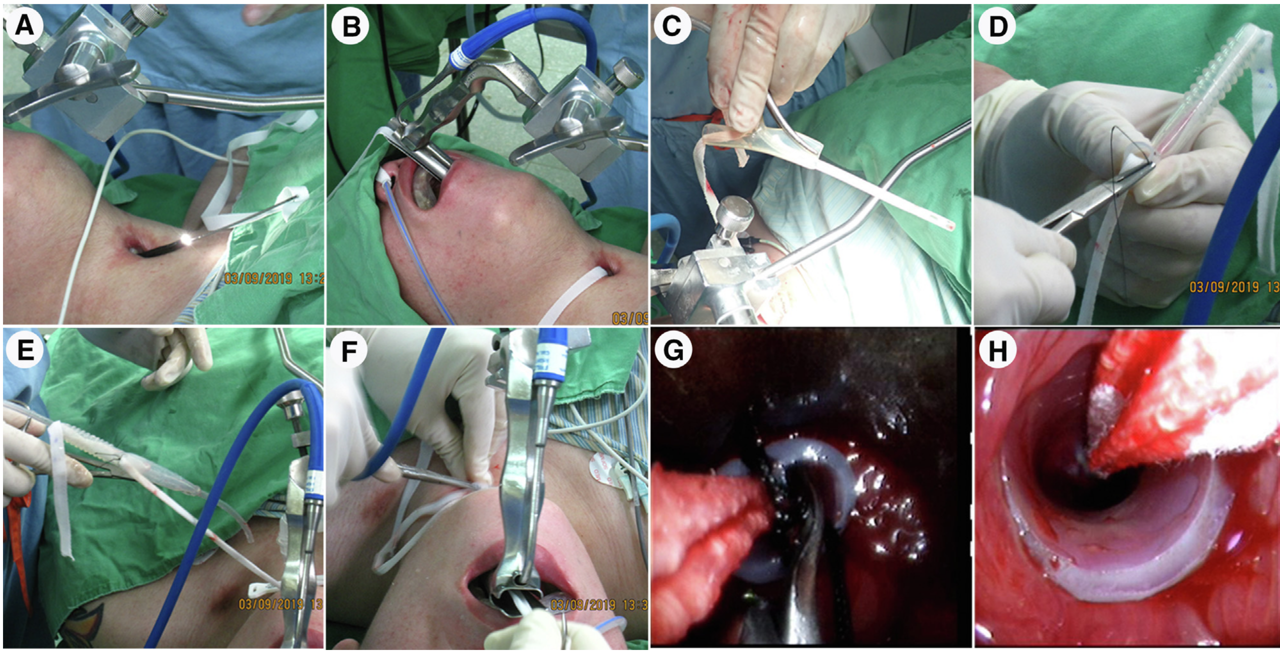


FIGURE 2. Innovative procedures for the intractable kinking of the upper arm of the T-tube with the intricate subglottic stenosis. A, In case of a hard stricture, quick retraction after tube withdrawal was noted after tracheal dilatation. We applied a flexible bronchoscope upward from the stoma, before gripping the tracheostomy tape with biopsy forceps (B) and having it withdrawn to the mouth's end. C, Inserting a tracheostomy tube for temporary ventilation, followed by inserting a T-tube with a tape-guiding upper arm and sputum suction tube guiding lower arm. D, In the event of a cicatricial stricture occurring due to the intractable kinking of the upper arm of the tapered T-tube, we harnessed a loose suture across the upper arm of the T-tube and taped it to the half-lumen for the purpose of tape immobilization. E, The procedure of insertion was performed similarly to the above description. We pushed the upper arm by bending the orifice of the tube toward the stoma and at the same time (F) applied an upward traction to the tape at the suture end to lightly snap the tube. G and H, Via use of a laryngoscope, we then used an endoscopic knife to remove the stitches spanning the tube lumen.

deviated trachea, torsion tract, or contracted stoma) in a tension-free manner. Upon full lubrication of both the inside and outside of the tube, a Kelly clamp was applied to the tip of the lower arm of the T-tube, which was then pushed together with an upward traction to reach the distal trachea. This procedure was performed until submergence and the snap of the tube occurred in an automatic manner (Figure 1, *G*).

(2) Upper-arm hard sitting using a 14F suction tube to guide the lower arm:

(a) Nonsuture holding the upper-arm to guide insertion of difficult sitting T-tube.

Step 7. a: Flexible bronchoscopy to guide the gripping of the tracheostomy tape. In the event of a hard stricture or deformity, a quick retraction after tube withdrawal was noted after tracheal dilatation. We applied a flexible bronchoscope with the tip positioned upward and outward from the stoma before gripping the tracheostomy tape with biopsy forceps and later withdrawing it to the end of the mouth (Figure 2, *A* and *B*). Step 7. b: T-tube insertion aided with a guided tracheostomy tape. After this procedure, we inserted a tracheostomy tube for temporary ventilation, followed by inserting a T-tube with a tape to guide the upper-arm in conjunction with the sputum suction tube guiding the lower arm (Figure 2, *C*).

(b) Suture holding the upper-arm guide for retractable stenosis with tube kinking:

Step 7. c: Suture holding tracheostomy tape. In the event of a cicatricial stricture occurring as the result of an intractable kinking of the upper-arm of the taper T-tube having tape mismatch, we harnessed a loose suture across the upper-arm of the T-tube and taped it to the half-lumen to immobilize the tape (Figure 2, *D*). The same procedure of insertion was performed as described above. Step 7. d: Difficult insertion of T-tube upper-arm with a simultaneous upward traction of the tape. We pushed the upper-arm by bending the orifice of the tube toward the stoma and at the same time exerted an upward traction to the tape at the suture

VIDEO 3. New T-tube insertion. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00302-4/fulltext.

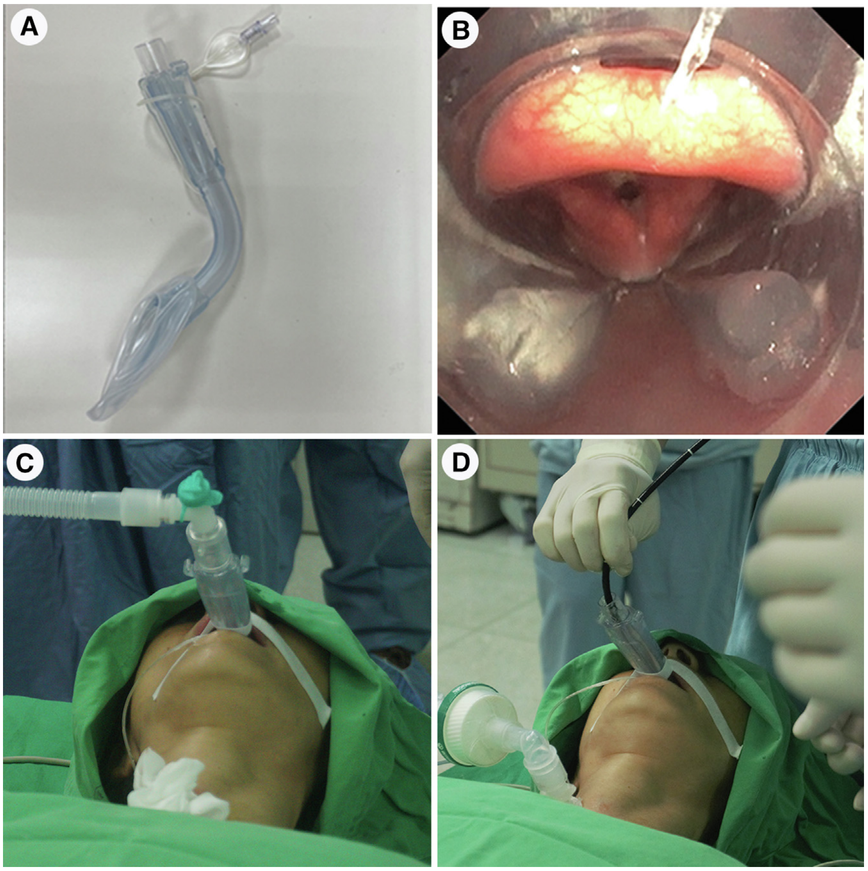


FIGURE 3. LMA-assisted T-tube revision and maintenance. A, Standard LMA feature. B, Fitting LMA with a clear view of the epiglottis and vocal cord. C, Ventilation through the LMA airway. D, Ventilation through the T-tube.

end to lightly snap the tube (Figure 2, *E* and *F*). Step 7 e: Removing the stitch via the mouth. By creating a tunnel using a fixed laryngoscope, we removed stitches spanning the tube lumen using an endoscopic knife (Figure 2, *G* and *H*). Step 8: Recovery from anesthesia at the operation. After confirming that the tube was in its proper position and the patient resumed normal breathing in the operating room (Figure 1, *H*), the patient was finally returned to the ward for further recovery from general anesthesia (Video 3).

Laryngeal mask airway (LMA). During follow-up, T-tube revision was performed to improve the surgical outcome or to remove the T-tube safely using LMA (Figure 3, *A*, Video 4). Here, the tight pharyngeal packing was able to prevent inspired gas leak through the upper end of the T-tube (Figure 3, *B*). In the event when the external branch of the T-tube was closed, a laryngeal mask was inserted for ventilation (Figure 3, *C*). The LMA was also for ventilation by occluding the extra-tracheal lumen of the T-tube through a spigot or used for upper airway occlusion, while allowing ventilation via the extra-tracheal portion (Figure 3, *D*).

Postoperative Care

T-tube care and patient education. The T-tube is typically not fixed to the skin unless the patient tends to grip the tube uncontrollably. A humidity of 100% is provided through a tracheostomy mask placed over the side-arm of the tube. This humidity is needed to prevent inspissation of secretions in the tube. Saline solution was instilled several times a day and suctioned or coughed out throughout the hospital stay. Patients were instructed to continue this procedure after hospital discharge (Video 5).

Bronchoscopy evaluation. Flexible bronchoscopy was performed immediately through the external arm on the first day after surgery. This was to evaluate and check the edge position, which could have been altered due to flexion or extension of the neck. The bronchoscopy also facilitated the removal of the inspissated materials. Furthermore, this allowed gathering of the necessary dynamic information on laryngeal mobility and malacia at the level of the proximal or distal airway. The demands on such a bronchoscopy depended on conditions of individual patients regarding a

VIDEO 4. LMA. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00302-4/fulltext.

VIDEO 5. T-tube care and education. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00302-4/fulltext.

secure tube patency and collecting information on the airway settings for tube removal.

Postoperative Follow-Up

T-tube maintenance and revision. In the special case of a subglottic stenosis extending close to the vocal cords, the T-tube must pass through the vocal cords to be effective. A tube so placed needs to end between the false and true cords without impinging on the epiglottis. If placed directly beneath the cords, irritation likely produces granulation tissue or edematous obstruction. The T-tube needs to be amended later, reshaped to fix any dilemma, to restore airway patency. The tapered tube above the vocal cord can be shifted to the shorter upper arm of the T-tube below the glottis 3 months after surgery.

Decannulation and closure of any remaining tracheal-cutaneous fistula. T-tubes were removed after 9 to 12 months, and if the stenosis persisted, a modified T-tube was replaced. If stenosis was resolved, the T-tube was directly removed. Patients required a secondary repair of the tracheal stoma only in the event of an existing tracheocutaneous fistula that was present after decannulation. The stomaplasty was conducted as described by Grillo.[19]

Outcome assessments. The primary outcome was 90-day mortality, and the secondary outcome was 90-day morbidity. Patients were followed up for 90 days, with their outcomes regarding mortality and morbidity being assessed, including complications directly related to the T-tube insertion. Good results were defined as having normal breathing and voicing; satisfactory results were having normal breathing and husky voicing but good enough for social communication. Failure results were those unable to tolerate the T-tube typically due to frequent aspiration or severe sputum inspissation. For all patients, their last follow-up visits were in November 2022.

Statistical Analyses

Our study samples included 42 patients. Descriptive statistics were presented as number (%) and mean (SD). Data (mean $\pm$ SD) were analyzed statistically using the Shapiro–Wilk test for normality.

RESULTS

Patients

A total of 42 patients were included in the study (mean age, 52.29 years; range, 9-84 years; 22 male [52.38%], 20 female [47.62%]). The mean length of hospital stay was 13.67 days (range, 2-45 days), with an average postoperative day of 10.48 (range, 1-41) days. The caregivers for these patients were themselves in 7 cases (16.67%), their relatives in 34 cases (80.95%), and from nursing homes in 1 patient (2.38%). The average duration of tracheostomy insertion was 4.8 (range, 1.3-83) months. Systemic diseases, detailed in Table 1, included central nervous system conditions in 29 patients, cerebral vascular accident in 13 patients, head injury in 8 patients, infection in 2 patients, hypoxic encephalopathy in 3 patients, and C-spine injury in 3 patients. Limb disability occurred in 15 patients, and cerebral vascular injury occurred in 10 patients, which involved coronary artery disease status of postoperation (S/P) operation in 7 patients, coronary artery disease S/P stent in 1 patient, rheumatic heart disease in 1 patient, and aortic dissection S/P operation in 1 patient. Respiratory conditions occurred in 12 patients, as chronic obstructive pulmonary disease in 4 patients, tuberculosis in 2 patients, bronchiectasis in 7 patients, and pneumonia in 4 patients. Diabetes mellitus occurred in 10 patients, hypertension occurred in 20 patients, malignancy occurred in 4 patients, renal insufficiency occurred in 6 patients, and 5 patients experiencing various conditions such as mediastinitis, burns, amyloidosis, parkinsonism, AIDS, and immunoglobulin G4–related tracheal disease (Table 1).

Primary Outcome

The details of primary outcomes are shown in Tables 2 and 3. We found no mortality at 90 days among patients who underwent the modified T-tube procedure treatment. Among all 42 patients, we gave T-tube stent treatments involving a tapered T-tube in 25 patients (8-10 mm in 2 patients [4.76%] and 10-13 mm in 23 patients [54.76%]) and standard T-tube treatments in 44 patients (11 mm in 15 [35.71%], 12 mm in 23 patients [54.76%], and 13 mm in 6 patients [14.29%]). A total of 11 patients (26.19%) experienced difficulty in T-tube insertion, necessitating suture holding at the upper arm.

Secondary Outcomes

The details of secondary outcomes are shown in Table 4. The average hospitalization stay was 13.67 days (range, 2-45). There was no adverse event directly related to the surgical procedure. Regarding the associated airways of these patients, airway lesion was supra-glottic (laryngomalacia) for 17 patients, with type I in 6 patients, type II in 7 patients, and type III in 4 patients. In addition, glottic (vocal cord) insufficiency was seen in 26 patients, with unilateral vocal cord palsy in 4 patients, bilateral vocal cord palsy in 1 patient, posterior commissure fibrosis in 6 patients, interarytenoid bridge adhesion in 3 patients, severe vocal cord synechia in 4 patients, and prominent edematous protrusion of ventricular mucosa in 3 patients. Substomatal tracheal stenosis occurred in 7 patients, substomatal malacia occurred in 5 patients, and bronchial stenosis occurred in 1 patient (Table 3). Complications included wound

TABLE 1. Demographics of variable manifestations of patients

Patient	No. (%)	Range (mean ± SD)
Gender		
Female	20 (47.62)	
Male	22 (52.38)	
Age (y)		9-84 (52.29 ± 19.37)
Duration of tracheostomy (mo)		1.3-83 (4.8 ± 1.9)
Postoperative days		1-41 (10.48 ± 7.28)
Hospital days		2-45 (13.67 ± 7.32)
Caregiver		
Patient	7 (16.67)	
Relatives	34 (80.95)	
Nursing home	1 (2.38)	
Systemic diseases		
Central nervous system condition	29 (69.05)	
Cerebral vascular accident	13 (30.95)	
Head injury	8 (19.05)	
Infection	2 (4.76)	
Hypoxic encephalopathy	3 (7.14)	
C-spine injury	3 (7.14)	
With limb disability	15 (35.71)	
Cerebral vascular condition	10 (23.81)	
Coronary artery disease S/P OP	7 (16.67)	
Coronary artery disease S/P stent	1 (2.38)	
Rheumatic heart disease	1 (2.38)	
Aortic dissection S/P OP	1 (2.38)	
Respiratory condition	12 (28.57)	
Chronic obstructive pulmonary disease	4 (9.52)	
Tuberculosis	2 (4.76)	
Bronchiectasis	7 (16.67)	
Pneumonia	4 (9.52)	
Diabetes mellitus	10 (23.81)	
Hypertension	20 (47.62)	
Malignancy* S/P	4 (9.52)	
Renal insufficiency	6 (14.29)	
Others†	5 (11.90)	

S/P OP, Status of postoperation. *Papillary carcinoma of thyroid, transitional cell carcinoma, thymus tumor, ovarian tumor, and adenocarcinoma of sigmoid colon. †Mediastinitis, burn, amyloidosis, parkinsonism, AIDS, and immunoglobulin G4–related tracheal disease.

infections in 3 patients, granulation in 16 patients, sputum inspissations in 21 patients, and pneumonia in 4 patients.

Long-Term Follow-Up

The operation times for patients were stratified into 3 categories with numbers of 1 to 2 for 10 patients (23.81%), 3 to 5 for 11 patients (26.19%), and more than 5 for 21 patients (50%). The additional procedures included T-tube revision and replacement, ablation of granulation tissue, and stomaplasty for persistent stoma after decannulation. The surgical outcomes were good in 29 patients (69.05%), satisfactory in 10 patients (23.81%), and failure in 3 patients (7.14%). Decannulation with patent lumen was found in 16 patients (38.10%). Persistent stoma after decannulation for cosmetic stomaplasty was found in 9 patients (21.43%) (Figure E3, *E*). Three patients (7.14%) were switched to Shiley tracheostomy. These observations were made at a median follow-up period of 6.2 years (range, 1.5-16.3 years) (Table 3). It was surprising to find that an 8- to 10-mm size of tapered T-tube was able to be placed near glottic and subglottic areas without irritation reported in selected patients (Figure E3, *C*).

DISCUSSION

Our practical experience of the modified T-tube procedure has been obtained from more than 1000 patients over a period of 20 years. Our experience is useful for honing skills on T-tube insertion. Currently, intricate subglottic stenosis close to the glottis remains one of the most challenging forms of treatment. Deeper insights into current treatment remain valuable. Laryngo-fissure typically performed by an ear, nose, and throat surgeon for T-tube insertion is complicated by voice changes. Otherwise, sleeve resection and reconstruction are conducted or alternated with rigid bronchoscope assistance for any problematic T-tube insertion by a chest surgery doctor. Our modified T-tube procedure has afforded a firm conviction of resilience and diversity with a critical comparison with the conventional technique (Table E1). Common indications of T-tube insertion are as follows: (a) temporary stenting of the airway; (b) definitive palliation of airway obstruction; (c) complications of airway reconstruction; (d) palliative management of tracheoesophageal fistula; and (e) severe inhalation burns. Our modified T-tube procedure can be more widely applied despite airway total occlusion complicated by local anatomic and systemic issues. The stenosis is situated over the upper half subglottic space abutting the vocal cord. Our method can be the priority of consideration with a high cost-performance ratio. Systemic factors including major comorbidity do not favor conventional surgery. We performed the procedure in the exact same manner as the initial procedure. With experience accumulation by honing the skills, we have refined the fixed laryngoscope to LMA for revision, replacement, or removal of the T-tube. The procedure produced less discomfort for patients and a more efficient assistance for general anesthesia.

Our modified and innovative T-tube insertion procedure provides several significant advantages: (1) Preoperation: Diversity in customized T-tube modifications overcomes all dilemmas devoid of the repositioning of the stoma[21]; (2) During surgery: The maneuverability of a fiber-optic bronchoscopy rather than a rigid bronchoscopy aids in grasping the tracheostomy tape for an upper-arm sitting, with sutures to immobilize the upper-arm and sputum

TABLE 2. Demographics of surgical maneuvers

Patient maneuver	No. (%)	Range (mean ± SD)
Operation time (min)		43-256 (73 ± 16.25)
No. of operations		
1-2	10 (23.81)	
3-5*	11 (26.19)	
>5*	21 (50.0)	
Nature of stenosis		
Soft	15 (35.71)	
Scarring	12 (28.57)	
Mixed	15 (35.71)	
Suture guide on upper arm of T-tube	11 (26.19)	
Stenosis length (cm)		0.8-6.3 (2.80 ± 1.20)
T-tube stent (n)		
Tapering (extra-long)		
8-10 mm	2 (4.76)	
10-13 mm	23 (54.76)	
Standard		
11 mm	15 (35.71)	
12 mm	23 (54.76)	
13 mm	6 (14.29)	
Upper arm (cm)		0.3-5.5 (2.55 ± 1.35)
Lower arm (cm)		2.9-8.2 (3.37 ± 0.57)

*Includes laser ablation of granulation tissue over upper or lower end of T-tube. Change to size 8- to 10-mm tapering T-tube. Can abut but not impinge on subglottic area, closure of persistent stoma, change new T-tube for revision or maintenance.

suction guiding the lower arm for speedy operation of the insertion; (c) Postoperation: The convenient maintenance of tube hygiene through instilling of an aseptic half saline packet, followed by coughing out inspissated materials accumulated all along the tube; and (d) Good results with long-term follow-up indicated that selected patients who tolerated the tapered 8- to 10-mm T-tube had spared irritation over the subglottic area leading to good voicing, because the vocal cord was bypassed.

Of note is a moderate stroke in a feeble patient who had received a nasogastric tube and tracheostomy tube. That was an absolute contraindication of the conventional open surgery. Those who underwent the modified T-tube procedure improved in their voicing and swallowing functions, although their mechanism remains to be determined. Moreover, boosting patients' motivation for general rehabilitation is a reward after nasogastric and T-tube removal, and that helps expedite their full recovery.

The multiple improvements on vocal cord function, speech, and swallow functions after T-tube insertion are summarized as follows: (1) Vocal cord function: Vocal cord rehabilitation with voice therapy on simple speech promoted recovery of the cord resilience; and (2) Swallowing function: Lifting of the tracheostomy cuff compression over esophagus and easing tracheostomy tape's external fixation restriction over the elevated glottis during swallowing improved swallowing function as assisted by normal closure of true or false vocal cord. Our experiences of T-tube placement have the following merits: (1) ease in detecting and treating glottis and subglottic problems, and (2) shortening the time of aspiration with smooth swallowing.

Complications of T-tube procedures involve the major and minor impacts. Major complications are aspiration and severe sputum inspissation. Precise location of T-tube placement should fulfill the principles of the following: (1) The proximal end of the T-tube should not abut the conus elasticus of the subglottic larynx; and (2) in special cases of subglottic stenosis, the T-tube must pass through the vocal cord and end between the false and true cords without impingement on the epiglottis. When the T-tube is placed above the vocal cord, the upper end shifts with neck flexion or extension, accompanied by hypertrophy of the arytenoid process. This would narrow the space between the false and true vocal cords, resulting in more chances of aspiration. Another advantage of our modified T-tube procedure is its easy revision for a perfect fit. Moreover, bacterial infections such as *Pseudomonas aeruginosa* could cause sputum impaction. Our modified innovative T-tube care was designed to minimize the risk (Video 4). Common minor complications include tracheostomy tube peristomal abscess or cellulitis, granulation or keloid formation, and persistent tracheocutaneous fistula after decannulation.

The paramount notion of using a 14F suction tube, inherent with optimal flexibility and diameter, guides the T-tube lower-arm insertion and is able to pass through even a shrunken stoma without any resistance due to its smaller size. This simple idea can be widely expanded and applied in a regular semi-rigid tracheostomy tube switching exercise and used as standard protocol of secure guiding. The core of the technique suggested that the most suitable protracted length is 10 cm below the orifice of the lower arm of the T-tube, with drawbacks of an inadequate length (like too long), which may cause kinking with resistance during tube withdrawal. When a guiding function diminishes in the case of a protrusion being too short, we advocate this feasible method as a form of standard assistance for a routine and tension-free tracheostomy tube replacement, thus setting it apart from standard T-tube insertion.

This concise and streamlined procedure is an improvement on tube revision both during surgery or later during follow-up because it is a less-demanding technique for both surgeons and anesthesiologists. Modifying the tube

TABLE 3. Demographics of surgical outcomes

Patient outcome	No. (%)	Range (mean ± SD)
Tube above the vocal cord	13 (30.95)	
Tube blow the vocal cord	29 (69.05)	
Complication		
Wound infection	3 (7.14)	
Granulation	16 (38.10)	
Sputum inspissation	21 (50.0)	
Pneumonia	4 (9.52)	
Persistent stoma	9 (21.43)	
Mortality	0 (0)	
Outcome		
Good*	29 (69.05)	
Satisfactory†	10 (23.81)	
Failure‡	3 (7.14)	
Follow-up		
Decannulation	16 (38.10)	
Shiley tracheostomy	3 (7.14)	
Follow-up time (y)		1.5-16.3 (6.2 ± 1.3)

*Good means normal breath and voice. †Satisfactory indicated normal breath but husky voice enough for social communication. ‡Failure means the T-tube not tolerated, mostly due to frequent aspiration or severe sputum inspissation, and changed to Shiley tracheostomy tube.

TABLE 4. Associated airway anatomy factors

Anatomy factor	No. (%)
Supraglottic (laryngomalacia)*	17 (40.48)
Type I	6 (14.29)
Type II	7 (16.67)
Type III	4 (9.52)
Glottic (vocal cord insufficiency)	26 (61.90)
Unilateral vocal cord palsy	4 (9.52)
Bilateral vocal cord palsy	1 (2.38)
Posterior commissure fibrosis	6 (14.29)
Interarytenoid bridge adhesion	3 (7.14)
Severe vocal cord synechia	4 (9.52)
Prominent edematous protrusion of ventricular mucosa	3 (7.14)
Substomatal tracheal stenosis	7 (16.67)
Substomatal malacia	5 (11.90)
Bronchial stenosis†	1 (2.38)

*Classification of laryngomalacia based on the site of supraglottic obstruction. Type 1, prolapse of mucosa overlying the arytenoid cartilages. Type 2, foreshortened aryepiglottic folds. Type 3, posterior displacement of the epiglottis.[20] †Tuberculosis with tracheal and bronchial (right) stenosis.

provides an exact fit for the obstructed airway for better outcomes. The customized commercial T-tube is reshaped by coining both ends of the tube through diverse options, mostly using a suitable size for the tapering T-tube in a standing or reversed position at a suitable length, and that devoids stoma of reposition. Furthermore, it can be tailored for lengthening or local widening by 2 different sized tube intussusceptions using a suture fixation.

The duration of decannulation is unpredictable, because it depends on local and systemic conditions. Long, high-grade, and complex laryngotracheal stenosis involves more than 1 subsite, particularly when associated with airway malacia and major laryngeal framework alterations. Decannulations were most successful with single-segment stenosis, with any cause of failure being contributed to by persisting local chronic inflammation extending to or developing new malacia over the subglottic or distal trachea. Patients with this condition require continual bronchoscopy maintenance using a long-size tube stent due to their vulnerable airways. Those with lesions involving the vocal cord or its adjacent area, as well as the long-segment tracheal stenosis, such as tuberculosis or immunoglobulin G4–related tracheal stenosis, require longer times to stabilize the airway for decannulation. One of our patients required 16 years before removal of the T-tube from the age of 9 to 25 years. Otherwise, among systemic factors the principal symptoms were primarily manifested by cord insufficiency together with a swallowing disorder, posing an asphyxia hazard, despite the intake cord morphology. Rehabilitation of swallowing function is a critical part of patient training for successful decannulation.

Study Limitations

Our study has several limitations. First, this is a preliminary study with a limited number of patients. Larger studies are needed for a better validated estimate for our technique. Second, along with many other surgical innovations, this is a monocentric and noncomparative study. Our results cannot be generalized without further evaluation involving multiple institutes.

CONCLUSIONS

The modified T-tube procedure treatment offers resilience and versatility in ablative bronchoscopy for streamlining the portfolio of procedures, achieving an outcome comparable with conventional surgery. For patients with an existing tracheostomy tube that is contraindicated for open surgical intervention, we propose the modified T-tube method used as the first line of definitive treatment.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: ablative bronchoscopy, modified T-tube procedure, total tracheal obstruction

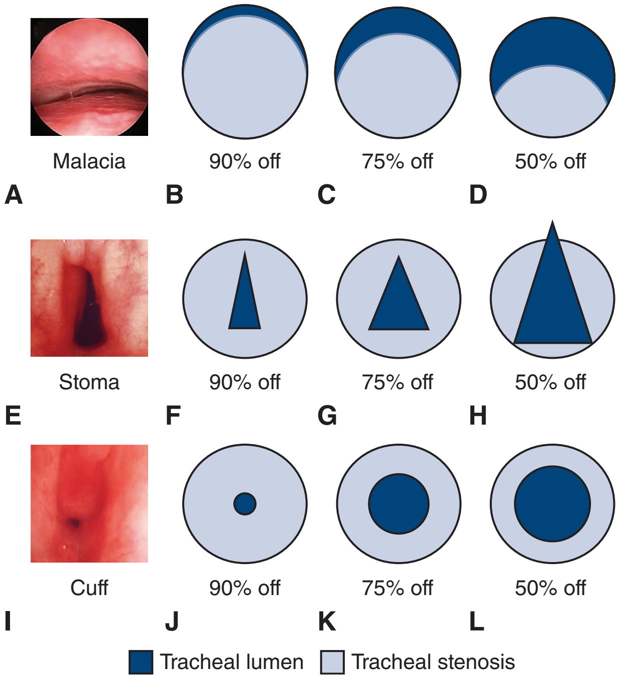

FIGURE E1. Geometry mapping of various degrees of the most common types of 3 tracheal stenosis. Patients with more than 50% lumen narrowing manifest dyspnea on exertion; aggravated stenosis more than 75% produces dyspnea and strider at rest, and is easily misdiagnosed as asthma or bronchitis. When airway strictures approach 90% lumen, critically life-threatening breathing appears. Precise computation with geometry mapping of the 3 major types of stenosis caused by the tracheal wall with damaged cartilage. A-D, Arrow-bow or fish-mouth type as symbol of malacia (dynamic stricture). E-H, Triangular or A-shaped with stoma sequelae. I-L, Circular-shaped (circumferential) feature with cuff induced (most severe).

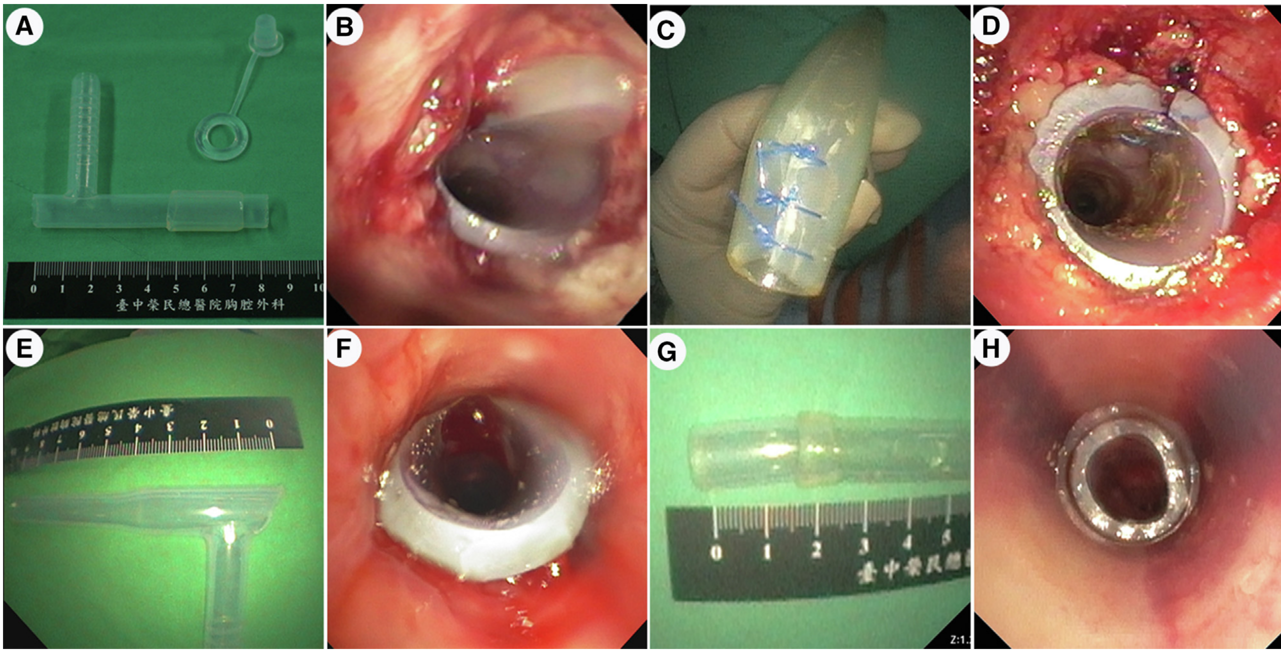

FIGURE E2. Versatilities of modification of a commercial T-tube tailor the underlying airway. A, Local widening of the tube with telescopic intussusception. B, Protruding anterior part at the end of the upper arm. C and D, Wedge resection at the end edge with suture approximation. E and F, Oblique shedding of the anterior part of the upper end. G and H, Elongation of the lower arm with partial telescopic intussusception with suture fixation.

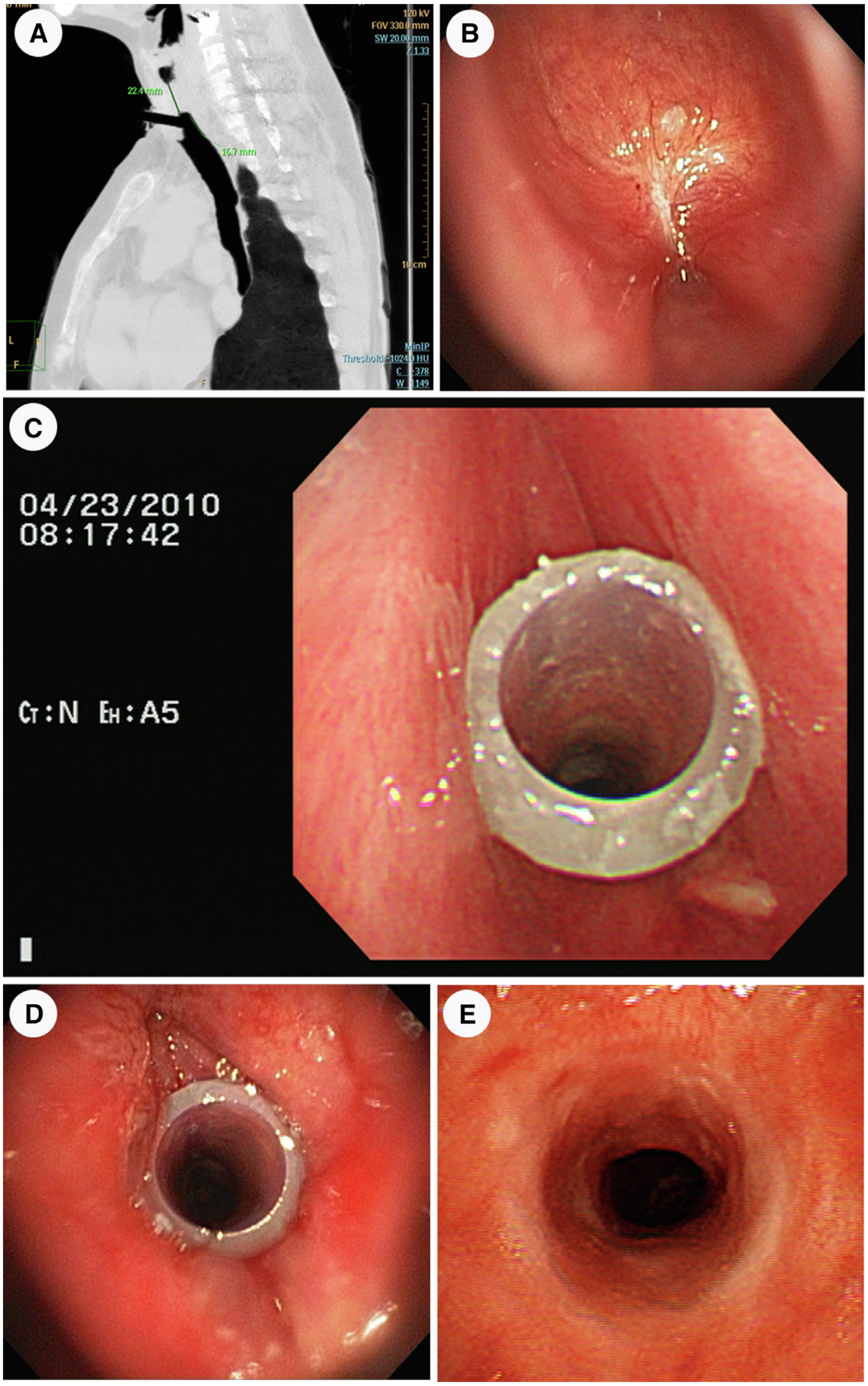

FIGURE E3. Paradigm of intricate subglottic stenosis complicated by a totally obstructed lumen both before and after treatment. A, Sagittal view computed tomography scan revealing a segment of 22.4-mm vanishing lumen below the vocal cord. B, Bronchoscopy disclosing a fibrotic obstruction with undetermined causality. C, An 8- to 10-mm tapering T-tube abuts the subglottic region with a clear voice without irritation. D, T-tube insertion followed by endoscopic management over 3 years. E, Patent lumen observed 6 months after decannulation.

TABLE E1. Comparison and competition of conventional T-tube and modified T-tube insertion

Section of application	Conventional T-Tube		Modified T-tube
	1. Otolaryngology	2. Thoracic surgery	Combination of 1 and 2
Surgical method	Laryngeal fissure	Can be assisted with rigid bronchoscopy	Noninvasive original stoma insertion with the aid of sputum suction tube and flexible bronchoscope
Anesthesia	Regular	High demanding	Regular
Operation time	Regular	Hard to control	Regular
		(Stoma scar tissue and angle deviation takes time)	(Concise and safe)
Surgical appearance	Obvious wound	Original tracheostoma	Original tracheostoma
Risks	The wound is susceptible to infection	Hypoxic time may be prolonged	Less
Results	Hard revision	Hard revision	Easy calibration and revision
Decannulation	Blindly remove	Precise	Precise
Quality of life	Good	Good	Good
Complication	Voice change	Rare	Rare
Indications	Strict	Strict	Less contraindication
		(Prognathous jaws, severely fixed cervical deformity, temporomandibular joint fixation after a stroke, or limited mouth opening capabilities due to previous oral surgery)	