Management of Congenital Tracheal Stenosis
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abstract

Congenital tracheal stenosis (CTS) is a serious and rare condition. In most cases, stenotic lesions are composed of complete tracheal rings of cartilage. The severity of symptoms correlates with the length of affected trachea, the presence of concomitant respiratory conditions, degree of luminal narrowing, and any bronchial involvement. Critically, CTS is a disorder that can lead to life-threatening respiratory insufficiency in children. Thus, it is a clinical entity that demands timely diagnosis and treatment. This review will firstly discuss the anatomy and pathophysiology of CTS and outline the various clinical presentations associated with the disorder. In addition, methods of diagnosis and treatment strategies will be reviewed, with a focus on contemporary surgical techniques. Finally, postoperative care of patients with CTS will be reviewed, and a contemporary multidisciplinary management approach will be presented.

Congenital tracheal stenosis (CTS) is a rare but potentially life-threatening disorder that often leads to severe respiratory insufficiency, particularly in neonates and infants. The true incidence of this complex anomaly is unknown given many infants die before the diagnosis is made.1 CTS represents a spectrum of stenotic airway lesions that are commonly composed of complete tracheal rings of cartilage that vary in location, length, and severity of luminal narrowing.1-3 The variability in clinical symptoms, diversity of associated cardiovascular anomalies, and scarcity of the disorder present significant challenges to its timely and effective management. The rarity and complexity of CTS demands a multidisciplinary therapeutic approach and individualized patient management.4

Although a subset of infants with CTS may outgrow their tracheal stenosis over time,2,5,6 surgical intervention is often inevitable for symptomatic patients. Several operative techniques for treating CTS have been described, including resection with end-to-end anastomosis,7 rib cartilage graft tracheoplasty,8,9 pericardial patch tracheoplasty,5,7,10,11 and slide tracheoplasty.4,5,7,12-17 Additionally, the use of endoscopic stenting as the primary treatment of CTS was recently reported.18 The purpose of this review is to (1) provide a comprehensive overview of the pathology, presentation, and treatment indications for CTS, (2) describe the available therapeutic options and their outcomes, and (3) outline a contemporary management approach for treating patients with CTS. We reviewed all articles published from Medline between 1964 and 2014 that were identified by using the following search terms: “congenital tracheal stenosis,” complete tracheal rings, tracheoplasty, or tracheal malformation. Secondary searches were conducted by using the terms trachea and diagnosis, “trachea and imaging,” and “endotracheal stent.” The year 1964 marks the first reported surgical repair of CTS.19
PATHOLOGY

CTS is characterized by a narrowing of the tracheal lumen, most commonly secondary to complete tracheal cartilage rings and an absent membranous trachea. Rarely, CTS is caused by irregular circular cartilaginous plates/ridges, or disorganized cartilage. Cantrell and Guild\(^\text{19}\) first described CTS, applying anatomic criteria to classify the anomaly into 3 morphologically distinct types: (1) generalized hypoplasia; (2) funnel-like stenosis; and (3) segmental stenosis (Fig 1). In type 1 CTS, the larynx is of normal diameter, whereas the entire length of the trachea is narrowed from the cricoid to the carina. In type 2 CTS, the subglottic tracheal diameter is of normal caliber; however, the trachea progressively narrows more distally, with the maximal point of constriction usually located just above the carina. In type 3 CTS, a short (2–5 cm) segment of the trachea is narrowed in an hourglass fashion. An additional classification system on the basis of functional symptoms was introduced in 2003,\(^\text{20}\) classifying CTS as (1) mild–asymptomatic or occasional symptoms; (2) moderate–respiratory symptoms, without respiratory embarrassment; and (3) severe–severe symptoms, including respiratory embarrassment. This system also includes an additional subclassification (A or B) to indicate the presence or absence of associated malformations. The global experience in managing CTS has demonstrated a strong correlation exists between anatomic type and functional category.

CTS is often associated with abnormal bronchial branching patterns. Commonly seen anomalous branching patterns include tracheal bronchus, bridging bronchus, bronchial trifurcation, and unilateral bronchial and lung agenesis. Tracheal bronchus (also referred to as “pig bronchus”) is an anomaly in which the origin of the right upper lobe bronchus is from the right lateral wall of the trachea.\(^\text{21}\) Bridging bronchus is a malformation wherein the right middle and lower lobes of the lung are supplied by a horizontal bronchus arising from the left main bronchus.\(^\text{22–24}\) Bronchial trifurcation involves tracheal division into 3 bronchi at the level of the carina. In children with unilateral lung agenesis, the trachea continues into the right or left main bronchus, with the contralateral bronchus being either absent or severely hypoplastic.\(^\text{25}\)

Isolated CTS is present in just 10% to 30% of patients,\(^\text{13,20,26,27}\) instead it is frequently associated with other cardiovascular and extrathoracic anomalies. Cardiovascular anomalies occur in up to 70% of patients\(^\text{13}\) and include pulmonary artery sling, patent ductus arteriosus, atrial septal defect, ventricular septal defect, atrioventricular septal defect, double aortic arch, partial anomalous pulmonary venous connection, Tetralogy of Fallot, complete transposition of the great arteries, and tricuspid atresia.\(^\text{28}\) The complexity of these associated anomalies often complicates the diagnosis of CTS and compounds operative risk.\(^\text{29}\) Associated extrathoracic congenital anomalies include gastrointestinal, renal, and skeleton abnormalities, including vertebral defects-anal atresia-cardiovascular anomalies-tracheoesophageal fistula with esophageal atresia-radial and renal dysplasia-limb defects/vertebral defects-anal atresia-tracheoesophageal fistula with esophageal atresia-radial and renal dysplasia syndromes and anorectal malformations.

CLINICAL PRESENTATION

The broad spectrum of stenotic lesions in CTS, ranging from short-segment tracheal narrowing to complete tracheobronchial hypoplasia, leads to a wide variability in clinical presentations. The severity of airway symptoms generally corresponds with the degree of airway obstruction.\(^\text{2}\) Based on the pattern and severity of symptoms, 3 groups of patients with CTS can be identified:

Minimal Symptoms/Incidental Finding

In this group, CTS is often diagnosed incidentally, or during workup for biphasic wheeze, a common presentation of mildly symptomatic patients.\(^\text{30,31}\) Some patients with mild stenosis may remain undiagnosed until late childhood or early adolescence, when there is often a tendency to develop exercise-associated respiratory difficulties. For these patients, thorough workup and diligent monitoring is warranted to determine an appropriate management strategy.\(^\text{6}\)

Symptomatic-Neonatal Period

This group of patients develops respiratory distress within the first hours to days of life. Presenting symptoms include stridor, cyanotic spells or coarse cough, and assisted ventilation is often required for critical respiratory insufficiency, particularly in the setting of complex associated cardiovascular malformations. These patients present the greatest challenge for clinicians, with severe associated congenital anomalies and concurrent respiratory infections often leading these patients to present in a critically ill state. The outcomes for
this group reflect this; studies have demonstrated 70% to 100% mortality in newborns with CTS who present in a critically ill state, with the major prognostic factor being the presence and severity of associated cardiovascular anomalies.\textsuperscript{2,20,29} The complexity of these patients demands a multidisciplinary management approach, including appropriate counseling of parents regarding the potential for poor outcomes.

**Symptomatic-Infancy**

This cohort usually presents with respiratory symptoms near the end of the first year of life, when physical activity increases. Symptoms of airflow limitation, including wheeze, exertional shortness of breath, and increased work of breathing become apparent. Some data suggest nonsurgical management is a feasible option because some children may outgrow their CTS;\textsuperscript{2} however, even just a minor respiratory infection can precipitate acute respiratory distress in these patients. Operative mortality for this group has been reported at 16% to 20%.\textsuperscript{29} Patients with Cantrell type 1 (generalized hypoplasia) CTS morphology are most likely to be severely symptomatic in the neonatal/early infancy period, and have a high rate of associated cardiovascular anomalies.\textsuperscript{29,32}

**DIAGNOSTIC EVALUATION**

Several diagnostic approaches have been used in patients with CTS, with some variability in practice patterns among major referral centers.\textsuperscript{3,33} The gold standard for definitive diagnosis of CTS is rigid laryngobronchoscopy under general anesthesia. Direct visualization of the airway enables accurate assessment of the length and diameter of the stenosed tracheal segment. Care should always be taken in performing rigid bronchoscopy; it requires general anesthesia, and minor mucosal damage may precipitate edema and critical obstruction in patients with severe airway stenosis. Some clinicians favor tracheobronchography; however, this is not widely used due to risk of inducing mucosal edema and causing respiratory decompensation.\textsuperscript{34} Others have advocated the use of virtual endoscopy to evaluate post stenosis bronchi and distal airway anatomy in patients with extreme airway narrowing. This approach uses high-resolution multirow detector computed tomography (CT) scanning to obtain high-resolution 3-dimensional endoluminal images to the level of the segmental bronchi.\textsuperscript{35} Contrast chest CT scans with 3-dimensional reconstruction is widely used to delineate major thoracic vessel and airway anatomy. However, this modality frequently underestimates the degree and length of airway narrowing, and hence should be used as an adjunctive investigative tool only.\textsuperscript{29} MRI has been demonstrated to be an effective and noninvasive imaging modality to delineate associated intracardiac and vascular anomalies in patients with CTS. However, the clinical characteristics of the CTS patient population often limits its utility; general anesthesia is often required to obtain an MRI in an infant or child, and patients with severe CTS are frequently intubated before undergoing investigations, thereby limiting accurate imaging of the native airway. Echocardiography is an important tool to exclude associated cardiac malformations. The clinical practices of major international referral centers have evolved to now include echocardiography in the diagnostic workup of all patients presenting with suspected CTS.\textsuperscript{13,33} Figure 2 outlines a diagnostic algorithm for the investigation of pediatric patients presenting with symptoms concerning for CTS.

**THERAPEUTIC APPROACHES AND TREATMENT INDICATIONS**

CTS is a complex disease process that demands a multidisciplinary therapeutic approach to successfully meet the diverse needs of a complicated patient population.\textsuperscript{3,34,36} The contemporary management of CTS at major tertiary centers involves an integrated, multidisciplinary team approach with expertise in cardiothoracic surgery, otolaryngology, cardiology, pulmonology, and anesthesiology.\textsuperscript{13,25,33} An important consideration is that inappropriate or untimely intervention has potential to precipitate a critical airway event in patients with CTS. This further emphasizes the importance of treating patients with CTS in a specialized, multidisciplinary center with the expertise and resources to deal with such a complication. Nevertheless, in the event that a child does present to an underresourced center with critical airway stenosis, extracorporeal membrane oxygenation support presents a suitable option as a bridge therapy. This strategy enables initial stabilization of the patient and facilitates transfer to a multidisciplinary center where the child can undergo definitive repair of his or her airway lesion.

Selection of an appropriate treatment strategy depends on the following: (1) the patient’s clinical status, (2) the severity and extent of the tracheal stenosis, and (3) the presence of associated congenital anomalies.\textsuperscript{20} Elliot et al\textsuperscript{3} described 4 key components that indicate the severity of CTS: (1) narrowness of the trachea; (2) extent of tracheal involvement; (3) bronchial involvement; and (4) the presence or absence of complete tracheal rings.

Until the 1980s, CTS was managed conservatively, with only a few groups reporting success with surgical intervention.\textsuperscript{19,37,38} The poor outcomes associated with early attempts at surgical repair led to a general consensus that CTS was not
amenable to operative repair; instead, many clinicians employed palliative strategies such as tracheostomy to treat CTS. There are some data to support the implementation of a conservative management strategy in a subset of patients with CTS who have been demonstrated to outgrow their tracheal stenosis by the age of 7 to 9 years. However, it is imperative that careful long-term clinical monitoring is employed, given a significant number of these patients will eventually require surgical intervention to treat worsening symptoms. Recently, the use of endotracheal stents as the primary treatment modality was reported in 5 patients with CTS; however, only modest outcomes were reported, with excessive granulation tissue formation and restenosis being major long-term complications. Nevertheless, the utility of adjunctive tracheal stenting to manage residual stenosis postsurgical intervention has been widely demonstrated.

Indications for surgery are primarily based on functional status, whereby any patient presenting with significant respiratory symptoms generally meets the criteria for operative intervention. Any combination of the following symptoms may be exhibited: persistent wheeze, dyspnea, repeated respiratory infections refractory to medical therapy, failure to wean from ventilator support, or unsuccessful ventilator support. A pediatric patient can typically tolerate up to 50% narrowing of the tracheal diameter before developing significant respiratory symptoms; therefore, overt respiratory symptoms are an important indicator for surgery. Although some early studies based their management approach solely on the degree of tracheal stenosis, the contemporary surgical treatment paradigm for CTS is fundamentally based on the clinical status of each individual patient.

SURGICAL TECHNIQUES AND OUTCOMES

Cantrell and Guild reported the first successful surgical repair of CTS in 1964 when they performed resection of a bridging bronchus with side-to-side anastomosis. The use of tracheal resection and primary anastomosis was further explored by Carcassonne et al in 1973, and others into the early 1980s. However, this procedure was found to be unsuccessful in treating patients with long-segment CTS. In response, implemented a tracheal graft technique to widen the airway diameter. Since then, numerous surgical reconstructive techniques have been described for CTS (Table 1). Current surgical options include the following: (1) resection and primary anastomosis; (2) patch tracheoplasty with nontracheal autologous tissue (costal cartilage, pericardium); (3) slide tracheoplasty; and (4) tracheal transplant with cadaveric tracheal homograft. Only the most frequently used techniques are described here.

Resection and Primary Anastomosis

Primary resection of the stenosed tracheal segment and primary reconstruction by end-to-end anastomosis is a suitable operative choice for patients with short-segment CTS (Cantrell type 3; Fig 3). Theoretically, this technique maintains a normal tracheal diameter; however, anastomotic tension may cause sutures to cut through, leading to fibrosis, scarring, and the potential for recurrent stenosis. Nevertheless, a number of reported series have demonstrated excellent outcomes using tracheal resection in selected patients with short segment tracheal stenosis.
rate of less than 9% has been reported for patients who have undergone primary resection and anastomosis, demonstrating the feasibility of this operative strategy for patients with short segment CTS.

**Patch Tracheoplasty**

**Rib Cartilage Tracheoplasty**

In 1982, Kimura et al reported the first successful repair of long segment CTS by using rib cartilage tracheoplasty in a 12-month-old child. Their technique consisted of reconstruction of the anterior tracheal wall by using 2 pieces of costal cartilage and was subsequently performed successfully in other centers.55,56 Jaquiss et al reported favorable outcomes in their series of 6 patients with CTS who underwent anterior tracheal reconstruction by using rib cartilage as the augmentation patch, reporting 1 case of graft dehiscence, and no deaths at 4.5 years follow-up. Despite a number of small series reporting satisfactory early outcomes,58–60 several serious complications were observed in patients treated with this technique. Complications included anastomotic leakage, necrosis, granulation tissue formation, and recurrent stenosis at the suture line. DeLorimier et al observed excessive granulation tissue formation when using rib cartilage graft ≥30% of the airway circumference. Furthermore, rib cartilage tracheoplasty was shown to be associated with high rates of reintervention for residual tracheal stenosis, and a high late mortality rate secondary to airway complications.61

**Pericardial Patch Tracheoplasty**

Idriss et al were the first to report the use of pericardial patch tracheoplasty in 5 patients with CTS. To perform this repair, cardiopulmonary bypass (CPB) is initiated, then a vertical incision is made into the stenosed tracheal segment, and a patch of harvested autologous pericardium is sutured in place. The final step is suspension of the patch to surrounding mediastinal structures to prevent collapse into the tracheal lumen. Advantages of this technique include the following: pliability of the pericardial patch, minimal dissection to expose the anterior tracheal surface, and establishment of an airtight suture line. Bando et al observed normal tracheal growth and epithelial development in the follow-up of 12 patients with CTS who underwent pericardial patch tracheoplasty. However, a major drawback of this technique is the formation of excessive granulation tissue arising from the devascularized surface of the pericardial patch. This frequently requires multiple bronchoscopic debriement procedures to remove excessive granulation tissue and enable reepithelialization to occur.52–66

To date, the most robust data on the pericardial patch tracheoplasty technique is derived from 2 series. Firstly, in 2001, Backer et al reviewed their long-term outcomes by using pericardial patch tracheoplasty to treat CTS. In their series of 28 patients, the mean postoperative length of stay was 60 days and there were 3 (6%) early deaths. Seven (25%) patients required reoperation or endoscopic stenting for residual tracheal stenosis and there were 5 (18%) late deaths.40 More recently, Fanous et al reported their long-term outcomes utilizing pericardial patch tracheoplasty in 26 patients with CTS. They reported 3 (11%) in-hospital deaths, whereas only 2 (9%) patients required late airway reintervention. All other survivors remained asymptomatic at a median follow-up of 11 years.

**Slide Tracheoplasty**

Tsang and Goldstraw first proposed a technique termed ”slide tracheoplasty” in 1989.
operation was initially performed in 2 infants with funnel-shaped tracheal stenosis; 1 died secondary to pulmonary infections, the other had a patent airway at 9 years post repair. A subsequent series of 4 patients was reported by Grillo, who augmented the technique to establish the contemporary slide tracheoplasty operation. In this procedure, the trachea is divided horizontally at the midpoint of the stenotic segment. The upper stenotic segment is incised vertically posteriorly, and the lower segment is incised anteriorly for the full length of the stenosis. The right-angled corners produced by these divisions are trimmed above and below, and the 2 ends are then slid over each other (Fig 4). The circumference of the stenosed segment is doubled, resulting in a quadrupled cross-sectional area.

Slide tracheoplasty has several advantages: (1) less risk of endoluminal granuloma formation; blood supply is preserved and the repair utilizes native tracheal cartilage lined with ciliated epithelium. This enables shorter postoperative intubation periods and fewer bronchoscopic reinterventions; (2) satisfactory tracheal growth post repair; (3) the technique is not limited by length of tracheal stenosis; (4) low incidence of anastomotic problems, including leakage, mediastinitis, fibrosis, or recurrent stenosis; and (5) a modified slide tracheoplasty can be successfully performed in all types of long-segment CTS, including patients with bronchial stenosis and tracheal bronchus anomalies. Numerous recent reports demonstrate slide tracheoplasty has lower mortality and postoperative airway complication rates compared with other techniques. In a series of 80 patients, Manning et al reported 4 deaths (5%) and airway reintervention in 23 (29%) patients at 12 months follow-up. Butler et al performed slide tracheoplasty in 101 consecutive patients; overall, 12 (12%) deaths occurred, with 45 (44%) patients requiring tracheal balloon dilatation and 22 (21%) undergoing tracheal stenting post initial repair.

CPB AND MANAGEMENT OF ASSOCIATED CARDIOVASCULAR ANOMALIES

Contemporary surgical management of CTS involves a median sternotomy approach and the use of CPB. For patients undergoing isolated tracheal surgery, single venous cannulation and normothermic CPB is a favored approach. Associated cardiovascular anomalies are most commonly repaired during the same procedure, typically before the tracheal repair. A frequently encountered concomitant cardiovascular anomaly is pulmonary artery sling. Patients with this anomaly usually undergo tracheal repair on CPB, followed by transection of the left pulmonary artery, relocation of the vessel anterior to the trachea, and reimplanted onto the main pulmonary artery. For associated intracardiac lesions, bicaval cannulation, moderate hypothermia, and cardioplegic arrest are surgical techniques that may be indicated depending on the specific cardiac anomalies being repaired.

POSTOPERATIVE CARE

The extreme heterogeneity and complexity of the CTS patient population presents difficult management challenges for clinicians. The standard of care for has evolved to an integrated, multidisciplinary team-based approach. Multidisciplinary, team-based care
Surgical Repair of CTS

Admission to CICU
- Intubation
- Support/secure endotracheal tube
- Mechanical ventilation
- Deep sedation
- Position head midline

Airway
- Stop paralytic
- Wean to pressure support
- Position head-midline
- Start dexamethasone 0.5 mg/kg 3 times per day, 24 h pre DLB

Exubation
- Performed at time of DLB (if patient’s level of sedation permits)

DLB
- Inspect tracheal anastomosis
- Adequate tissue healing?

No
- Stay intubated
  - Sedation
  - Position-keep head midline
  - Repeat DLB

Post Exubation
- Regular saline nebulizers
- Humidified O₂
- Continue dexamethasone 0.5 mg/kg 3 times per day for 24 hours post extubation

Commence oral feeding
- Clear liquids to soft solids
- Progress diet as tolerated
- Echocardiogram predischarge if underwent concomitant cardiovascular procedure

Flexible Laryngoscopy
- Before feeding by mouth
  - View vocal cords
  - Normal vocal cord function?

No
- Feeding Evaluation
  - Feeding Team: Speech pathologist, nutritionist
  - ≥ Modified barium swallow
  - Nutrition as per Feeding Team recommendations; thickened feeds, naso-gastric feeding

Follow-up
- If underwent concomitant cardiovascular surgery: cardiology clinic follow-up
- DLB at 4 weeks post surgery (earlier if symptomatic)
  - DLB to assess for presence of tracheal stenosis at anastomosis site

No
- 6 weeks

Bronchial Dilatation
- Rigid bronchoscopy
- Balloon dilatation ± local steroid injection/inhaled budesonide
- Dexamethasone 0.5 mg/kg for 24 hours post dilatation

Review in ORL clinic
(Sooner if clinical concern or symptomatic)
- Repeat DLB to assess for tracheal stenosis at anastomosis site

4 weeks

Repeat DLB
- Repeat dilatation if required

ORL follow-up as required
- Return if airway symptoms develop

FIGURE 5
Postoperative management protocol for CTS. CICU, cardiac intensive care unit; ORL, otolaryngology.

has significantly improved perioperative outcomes in patients with CTS, reducing the duration of mechanical ventilation, and length of ICU and hospital stay. Several centers have evolved their postoperative management to favor earlier extubation of patients with CTS. Many perform bedside fiberoptic
bronchoscopy at 24 to 48 hours postsurgery to facilitate earlier wean from mechanical ventilation.\textsuperscript{13,33} Currently, no established protocol exists for postoperative management. Herein is a multidisciplinary management algorithm to help guide postoperative care (Fig 5) of patients with CTS. Major postoperative airway complications include anastomotic breakdown with subsequent air leak, tracheal narrowing secondary to excessive granulation tissue formation or restenosis at the suture line.

Post discharge, any child presenting with symptoms of airway narrowing should undergo evaluation with direct laryngoscopy and bronchoscopy. If significant tracheal restenosis is present, rigid bronchoscopic balloon dilatation of the stenosed segment is performed. In children who develop excessive granulation tissue at the anastomotic site, local steroid injection has been somewhat effective in reducing further granulation tissue and stenosis. The role of topical application of mitomycin-C continues to be evaluated.\textsuperscript{71,72} Moreover, recent studies have demonstrated that inhaled budesonide can also be somewhat effective in reducing excessive granulation tissue post CTS repair.\textsuperscript{73,74}

**CONCLUSIONS**

CTS is an important pediatric anomaly that often presents as a life-threatening emergency. Timely and effective treatment of CTS is often challenging due to the diversity of clinical presentations, complex associated anomalies, and rarity of the disorder. Optimal outcomes are achieved by managing patients with CTS in specialized centers that have a focused interest and multidisciplinary expertise. Slide tracheoplasty is now recognized as the procedure of choice, irrespective of airway anatomy and length of tracheal stenosis, whereas segmental resection and anastomosis is a viable treatment option in the subset of patients with CTS with discreet, short-segment stenosis. Postoperative airway stenosis is routinely managed by using endoscopic balloon dilatation techniques. Tracheal stenting may also be used as an adjuvant therapy, yet this strategy carries its own additional morbidity and is currently only used as salvage procedure. Nevertheless, tracheal stenting shows promise to become a more feasible adjunctive therapy, with recent reports demonstrating novel new technologies, such as bioabsorbable materials\textsuperscript{75} and 3-dimensional printer derived devices,\textsuperscript{76} can be used to design airway stents that are anatomically specific for a given patient.

**ABBREVIATIONS**

CPB: cardiopulmonary bypass
CTS: congenital tracheal stenosis

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