

Tracheobronchomalacia and Excessive Dynamic Airway Collapse: Current Concepts and Future Directions

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Abbreviations: COPD = chronic obstructive pulmonary disease, ECAC = expiratory central airway collapse, EDAC = excessive dynamic airway collapse, TBM = tracheobronchomalacia, TBP = tracheobronchoplasty, 3D = three-dimensional

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Define the current accepted standards for diagnosis of ECAC.
- Recognize the imaging appearance of TBM and EDAC.
- Outline treatment options for patients with ECAC.

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Tracheobronchomalacia (TBM) and excessive dynamic airway collapse (EDAC) are airway abnormalities that share a common feature of expiratory narrowing but are distinct pathophysiologic entities. Both entities are collectively referred to as expiratory central airway collapse (ECAC). The *malacia* or weakness of cartilage that supports the tracheobronchial tree may occur only in the trachea (ie, tracheomalacia), in both the trachea and bronchi (TBM), or only in the bronchi (bronchomalacia). On the other hand, EDAC refers to excessive anterior bowing of the posterior membrane into the airway lumen with intact cartilage. Clinical diagnosis is often confounded by comorbidities including asthma, chronic obstructive pulmonary disease, obesity, hypoventilation syndrome, and gastroesophageal reflux disease. Additional challenges include the under-recognition of ECAC at imaging; the interchangeable use of the terms *TBM* and *EDAC* in the literature, which leads to confusion; and the lack of clear guidelines for diagnosis and treatment. The use of CT is growing for evaluation of the morphology of the airway, tracheobronchial collapsibility, and extrinsic disease processes that can narrow the trachea. MRI is an alternative tool, although it is not as widely available and is not used as frequently for this indication as is CT. Together, these tools not only enable diagnosis, but also provide a road map to clinicians and surgeons for planning treatment. In addition, CT datasets can be used for 3D printing of personalized medical devices such as stents and splints.

*An invited commentary by Brixey is available online.
 Online supplemental material is available for this article.*

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Introduction

Exaggerated tracheobronchial narrowing during expiration is termed *expiratory central airway collapse* (ECAC) and includes two distinct entities: *tracheobronchomalacia* (TBM) and *excessive dynamic airway collapse* (EDAC) (1). These terms have often been used interchangeably in the medical literature, contributing to confusion. TBM occurs as a result of cartilaginous weakening, whereas EDAC is characterized by “membranous malacia” and results in excessive anterior displacement of the lax posterior membrane into the airway lumen on expiration, with normal tracheal cartilage (Fig 1). EDAC is often associated with atrophy of smooth muscle fibers of the trachealis muscle in the membranous portion of the trachea. The true prevalence of ECAC (TBM and EDAC) is difficult to determine, given that this is an underrecognized condition with overlapping symptoms at clinical presentation, comorbidities, and a lack of standardized diagnostic criteria. Studies (2–6) have reported a prevalence of up to 5% in patients undergoing bronchoscopy, although the estimate increases to 13% in those with pulmonary issues and to 37% in those with chronic obstructive pulmonary disease (COPD) and airway disorders.

TEACHING POINTS

- TBM occurs as a result of cartilaginous weakening, whereas EDAC is characterized by “membranous malacia” and results in excessive anterior displacement of the lax posterior membrane into the airway lumen on expiration, with normal tracheal cartilage.
- TBM is characterized by abnormality of the tracheal and/or bronchial cartilage and is classified by the location of the abnormality, including tracheomalacia (ie, limited to the trachea), bronchomalacia (ie, limited to the bronchi), or TBM (ie, involving the trachea and bronchi).
- Multidetector CT also allows assessment of adjacent structures and helps in the evaluation of other potential causes that may be contributing to a patient’s symptoms (eg, extrinsic compression, COPD, bronchiectasis, recurrent aspiration, or hiatal hernia).
- The severity of expiratory collapse is graded as mild (70%–80%), moderate (81%–90%), or severe (>90%), with definitive treatment typically reserved for narrowing of greater than 90%.
- TBP is considered for patients with EDAC who are good candidates for surgery, have received optimal medical treatment, and have substantial improvement in symptoms after a stent trial.

The purpose of this review article is to discuss the current understanding of the disease processes of ECAC, the challenges and controversies in its diagnosis, and the role of cross-sectional imaging. We discuss the imaging appearance, suggested protocols, and common associated conditions. A brief overview of treatment options and development of advanced treatment options with an imaging focus is also detailed. Because several features and management options for TBM and EDAC overlap, we will use the term *ECAC* to include both entities (unless TBM or EDAC is specified).

Classification

Classification is based on the extent and morphology of ECAC (7). Findings may be diffuse or segmental and may involve only certain portions of the tracheobronchial tree (8). EDAC, also referred to as *membranous or posterior malacia*, is characterized by a normal configuration of tracheal cartilage, with exaggerated inward bulging of the posterior membrane. TBM is characterized by abnormality of the tracheal and/or bronchial cartilage and is classified by the location of the abnormality, including tracheomalacia (ie, limited to the trachea), bronchomalacia (ie, limited to the bronchi), or TBM (ie, involving the trachea and bronchi). TBM is further classified into three different types on the basis of the morphology of the collapse, including (*a*) the crescent type, which is abnormal anterior tracheal cartilage, leading to narrowing in the anteroposterior dimension (Figs 1C, 2A, 2B); (*b*) saber-sheath TBM, which

is weakening of the lateral aspects of the cartilage, resulting in narrowing in the transverse dimension (ie, side to side) (Fig 2C, 2D); and (*c*) circumferential TBM, which is a diffuse abnormality of the tracheal cartilage, resulting in circumferential narrowing (Fig 2E, 2F).

Etiology of ECAC

ECAC can be congenital or acquired. Table 1 lists common causes of and associations with ECAC.

Congenital

Congenital ECAC is usually a result of impaired maturation of cartilage, which causes weakness of the tracheobronchial wall and supporting structures and leads to increased compliance and excessive expiratory collapsibility of the trachea and bronchi (9). It can also be associated with other conditions including glycogen storage diseases (eg, mucopolysaccharidoses), chromosomal anomalies (eg, trisomy 9 and 21), bronchopulmonary dysplasia, and connective tissue disorders (eg, Ehlers-Danlos syndrome) (10). It is the most common congenital anomaly of the central airways and typically manifests in patients in infancy or childhood.

Acquired

Acquired ECAC results from a variety of inflammatory, infectious, and traumatic processes, leading to degeneration of normal cartilage or atrophy of smooth muscles in the membranous portion of the trachea.

Relapsing polychondritis and recurrent infections (eg, chronic bronchitis or cystic fibrosis) cause chronic inflammation and eventually lead to destruction of cartilage, contributing to expiratory collapse in more than one-half of patients (approximately 56% of patients with relapsing polychondritis), although symptoms are only present in 14% of patients with relapsing polychondritis (10,11).

Trauma, especially iatrogenic injury from tracheostomy or prolonged endotracheal intubation, is one of the most common causes of ECAC. Other causes include external compression of the trachea from a multinodular goiter, malignant or benign lesions of the neck and mediastinum, and vascular compression from aneurysmal disease or congenital cardiac disease (2).

Conditions such as COPD, asthma, and obesity are also known to contribute to EDAC (Fig 3). These associations are important to recognize, given the high prevalence of COPD in the general population, and radiologists must be vigilant when interpreting images from examinations performed for other reasons. One of the reasons for this association is postulated to be respiratory mechanics. Some authors believe that EDAC in patients with COPD and asthma is a manifestation of

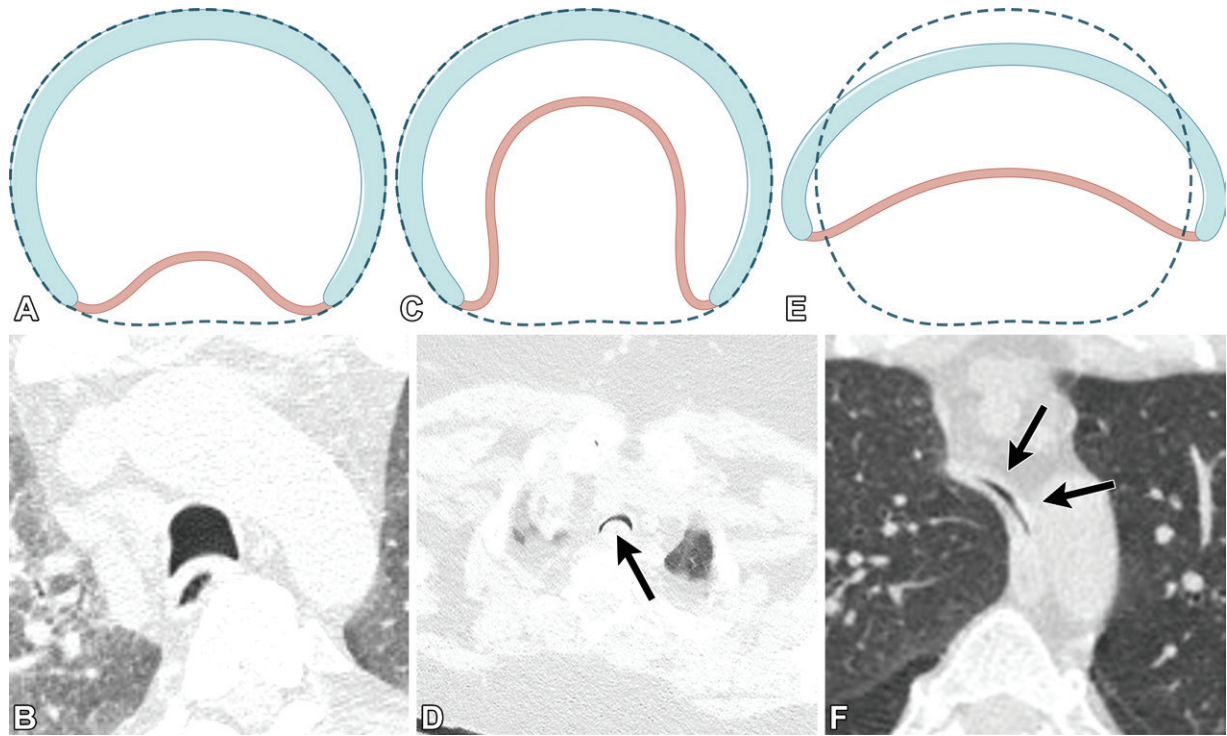


Figure 1. Illustrations (A, C, E) and axial chest CT images (B, D, F) in forceful exhalation show the appearance of the normal trachea (A, B), excessive dynamic airway collapse (EDAC) (C, D), and tracheomalacia (E, F). Note the exaggerated bowing of the posterior membrane (arrow in D), with preserved integrity of the tracheal cartilage in EDAC. In comparison, tracheomalacia results in flattened tracheal cartilage (arrows in F).

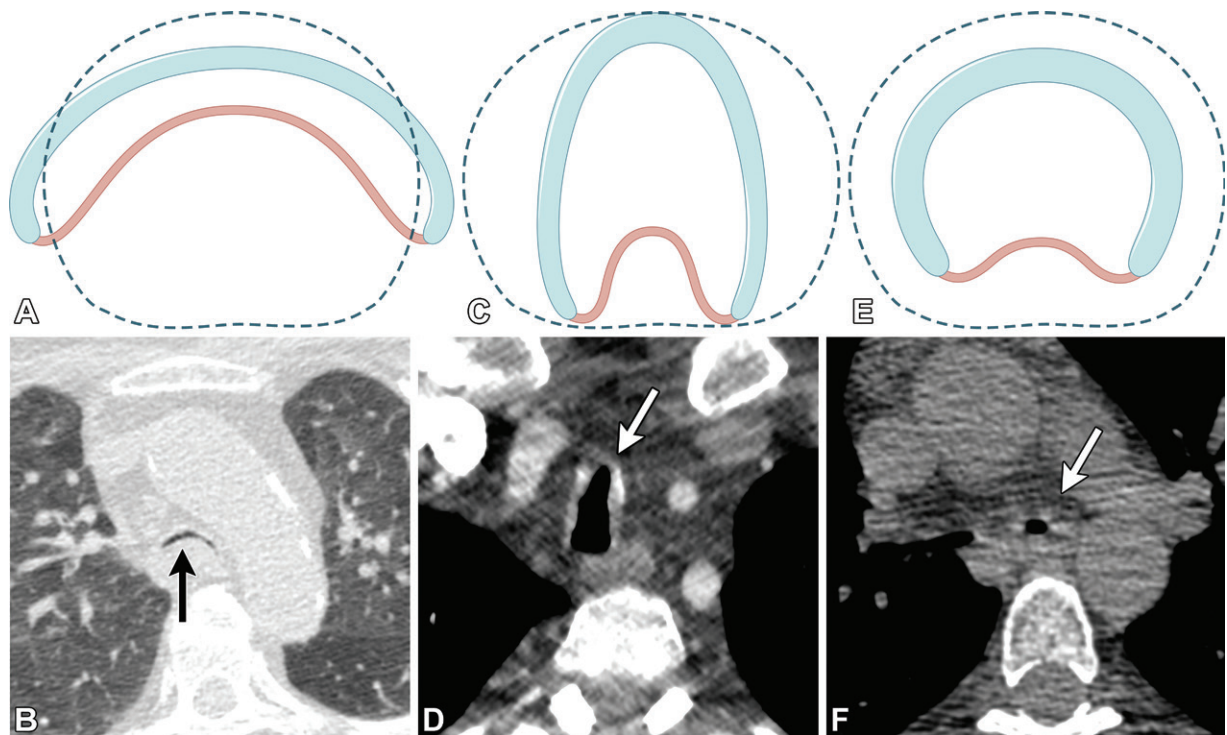


Figure 2. Classification of tracheomalacia. (A, B) Illustration (A) and axial CT image (B) in dynamic expiration (lung window) show crescent-type TBM with abnormal flattened anterior tracheal cartilage and exaggerated bowing of the posterior membrane (arrow in B). This patient has both tracheomalacia and EDAC. (C, D) Illustration (C) and axial CT image (D) show saber-sheath TBM with weakening of the lateral aspects of the tracheal cartilage, leading to side-by-side narrowing (arrow in D) in the expiratory phase. (E, F) Illustration (E) and axial CT image (F) show circumferential bronchomalacia and global abnormality (arrow in F) of the left main stem bronchial cartilage in the expiratory phase.

obstructed peripheral airways, and therefore, EDAC is a marker of the severity of COPD or asthma rather than a true pathologic stand-alone process. Involvement of the small airways in patients with COPD, asthma, or obesity results in a decrease in pressure, which, in conjunction with increased pleural pressure during expiration (accentuated in patients with morbid obesity), leads to an increase in the transmural pressure gradient. This causes collapse or narrowing downstream from the small airway obstruction. During expiration, the central large airways, which are downstream from the small airways, are collapsible (the posterior membrane being the weakest point), resulting in EDAC. The supporting argument for this hypothesis is the observation that EDAC often improves or resolves after a lung transplant in patients with COPD (12). Notably, this discussion of ECAC and its association with COPD or asthma pertains primarily to EDAC and not to TBM, which is an intrinsic abnormality of the cartilage itself. Hence, treatment should always be focused on optimization of underlying disease processes first, before specific treatment of ECAC is considered.

There is also a described association between the use of corticosteroids and ECAC in patients with asthma and COPD (13). One of the postulated mechanisms is vasoconstriction induced by steroids, which causes a reduction in the airway mucosal flow. The use of systemic steroids may result in atrophy of tracheal smooth muscle and reduction in the number of epithelial cells, which may be contributors to EDAC (14,15). However, because of the retrospective nature of these reports, it is difficult to ascertain the causality between steroid use and ECAC, and it is possible that this association may simply be a manifestation of the underlying severity of disease (16). Because steroids are indicated in patients with severe disease to reduce inflammation, the association between steroid use and ECAC may be related to the severity of COPD or asthma, rather than to the deleterious effects of steroids (Fig 3).

Clinical Presentation

Diagnosis of ECAC is challenging and requires a high level of clinical suspicion. Patients are often asymptomatic or may have nonspecific symptoms and overlapping comorbidities (17). The severity of symptoms progressively worsens as the degree of TBM increases (1).

The major symptoms of ECAC in adults are dyspnea, cough, inability to clear secretions, and wheezing that can worsen in the recumbent position (3,18). Paroxysms of coughing with a “barking” character have been described (19), presumably because of vibration of the posterior membrane against the tracheobronchial cartilage.

Table 1: Common Causes of and Associations with ECAC

Congenital	
	Storage disease (mucopolysaccharidosis)
	Chromosomal anomalies (trisomy 9 and 21)
	Bronchopulmonary dysplasia
	Connective tissue disorder (Ehlers-Danlos syndrome)
Acquired	
	COPD
	Asthma
	Obesity
	Inflammation (relapsing polychondritis, radiation therapy)
	Repeated infections
	Posttraumatic (prolonged intubation, tracheostomy)
	Mechanical (extrinsic compression from a mass or lymph node, vascular anomalies, pectus excavatum)

The increased flaccidity of the trachea and bronchi prevents normal clearance of secretions and may lead to recurrent infections and bronchiectasis (19).

Complete pulmonary function tests including measurement of respiratory volumes can reveal obstructive or restrictive changes but may be normal in up to one-fifth of these individuals (3).

Role of Imaging in Diagnosis

The current reference standard for diagnosis of TBM is flexible dynamic bronchoscopy, because it allows real-time examination of the airways and provides accurate assessment of the morphology, the degree of TBM, and the extent of airway abnormality. Cross-sectional imaging, especially CT, has been used increasingly as a noninvasive imaging tool to confirm the diagnosis, with accuracy of 93%–97% (20,21). Multidetector CT also allows assessment of adjacent structures and helps in the evaluation of other potential causes that may be contributing to a patient’s symptoms (eg, extrinsic compression, COPD, bronchiectasis, recurrent aspiration, or hiatal hernia) (22).

In addition to its use in diagnosis, imaging can help surgeons and interventional pulmonologists in planning therapeutic interventions and in personalizing treatment options such as patient-specific three-dimensionally (3D) printed tracheal splints.

Imaging Technique

CT Protocol

CT should ideally be performed with a multidetector helical CT scanner with 16 or more detector rows. The standard protocol includes

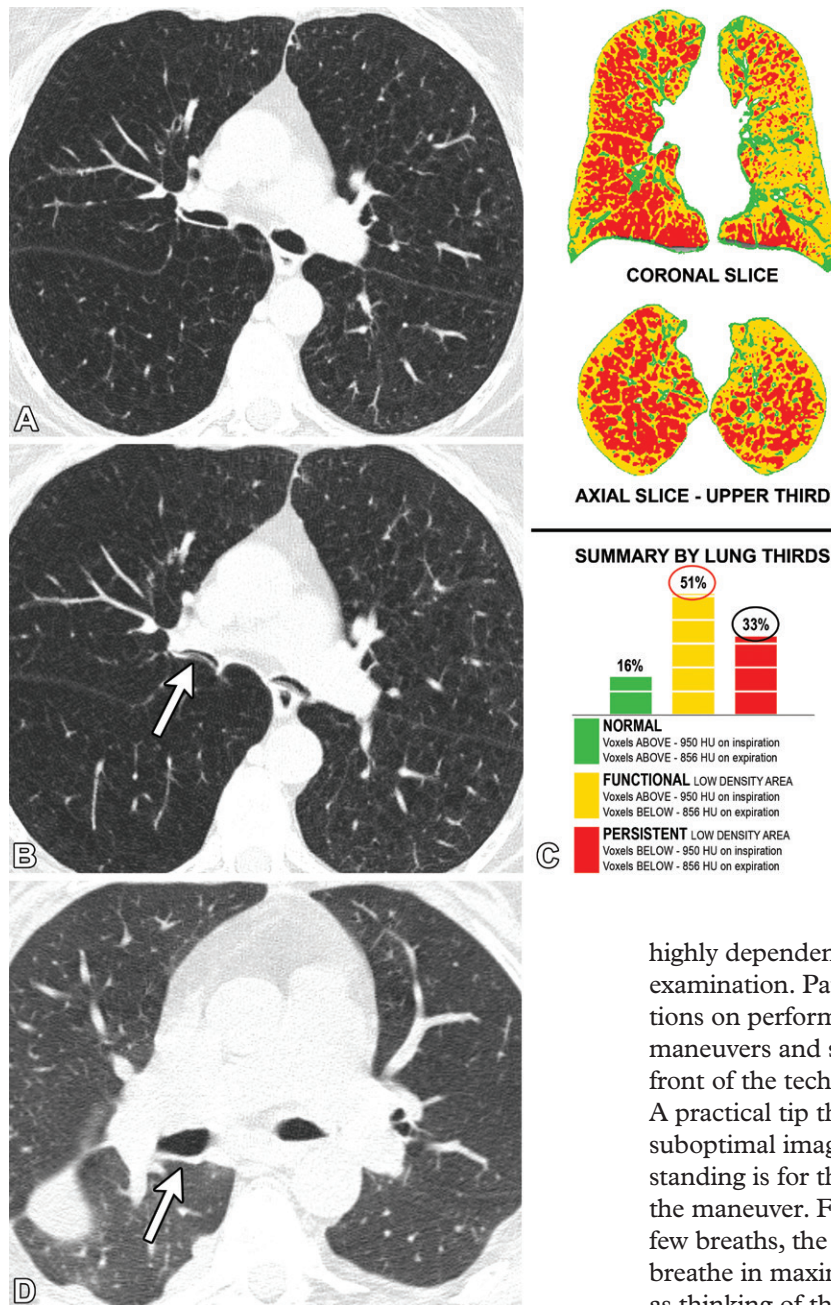


Figure 3. EDAC occurring in association with COPD in a 63-year-old woman with a history of α 1 anti-trypsin deficiency. (A) Axial thin-section CT image acquired at end inspiration shows panlobular emphysema. (B) Axial thin-section CT image acquired in end expiration shows severe air trapping, with EDAC involving the bronchi (arrow). The study was performed for quantification of emphysema and air trapping, and hence, the expiratory scan was timed for end expiration. (C) Lung density analysis shows that 51% of the lungs is affected by air trapping (red circle) and 33% by emphysema (black circle). (D) Thin-section CT image acquired in end expiration after the patient underwent lung transplant shows resolution of bronchial collapsibility (arrow).

imaging the central airways during two different phases of respiration: the end inspiratory phase (ie, imaging during suspended end inspiration) and the dynamic expiratory phase (ie, imaging during forceful exhalation) (23–26). The low-dose expiratory scan for large airway disease is preferably done during forceful exhalation, unlike standard thin-section chest CT protocols that use end expiratory imaging for assessment of small-airway diseases and air trapping. This is because the large airways are most collapsible during dynamic forced expiration, and the disease severity can be underestimated with standard thin-section CT examinations (Fig 4, Movies 1–3). The diagnostic quality of dynamic CT of the trachea is

highly dependent on coaching the patient before examination. Patients should receive clear instructions on performing the inspiratory and expiratory maneuvers and should practice several times in front of the technologist before the actual scan. A practical tip that can reduce the likelihood of suboptimal images and improve patient understanding is for the technologist to demonstrate the maneuver. For the inspiratory scan, after a few breaths, the patient should be instructed to breathe in maximally. Providing visual cues, such as thinking of the lungs as balloons that must be filled with maximum air, can help the patient to understand the effort needed for a good inspiratory scan. Also, patients should be instructed to avoid performing the Valsalva maneuver during the end of the inspiratory maneuver because it raises intrathoracic pressure and leads to suboptimal imaging by introducing motion artifact. After a pause of a few short normal breaths, the patient should attempt the expiratory maneuver with clear instructions (ie, emptying the lungs maximally). The timing of the CT scan should be coordinated to image during the patient’s forceful exhalation. Pursing of the lips should be avoided, because it gives a false sensation of maximal expiratory effort by slowing the emptying of the lungs (27). The patient’s inability to follow breathing instructions can render the study nondiagnostic for evaluation.

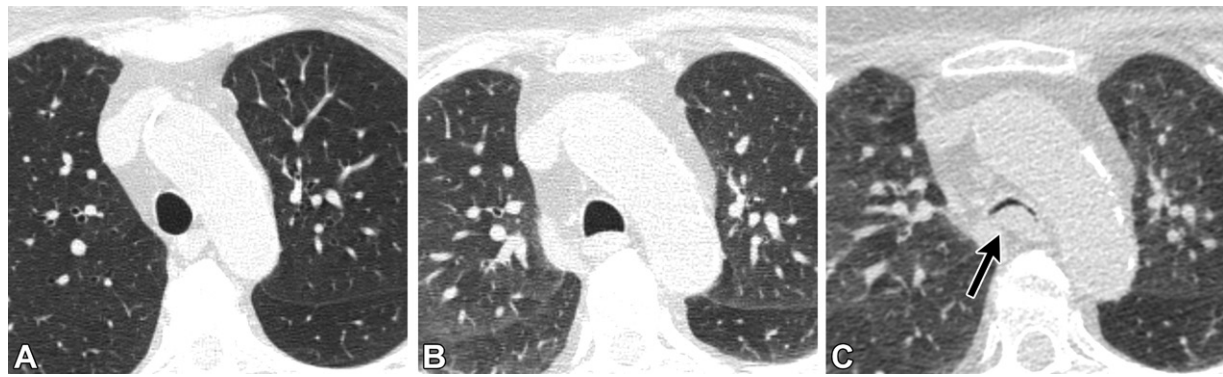


Figure 4. Recurrent bronchitis and pneumonia from underlying common-variable immunodeficiency in a 74-year-old woman. Inspiratory (A), end expiratory (B), and dynamic expiratory (C) phase axial chest CT images show no substantial reduction in the cross-sectional luminal area in B. EDAC was not visible at end expiration but is readily apparent in C (arrow in C).

CT measurements of forced expiratory tracheal collapse have been shown to be highly reproducible over time, with proper technique (28).

In infants and young children who may not be able to follow respiratory instructions and require general anesthesia, the study is typically performed with intubation and controlled ventilation for inspiration and end expiration (19). Free-breathing cine CT (eliminating the need for the patient to follow respiratory instructions), general anesthesia, and controlled ventilation have also been evaluated in some studies (29). Some authors (19) have suggested combining cine CT with the coughing maneuver. Cine CT is being evaluated and holds promise, given the 16-cm craniocaudal coverage that is now possible with volumetric 320-detector-row CT scanners.

Before helical scanning, initial scout topographic images are obtained to determine the area of coverage. Inspiratory scans are useful for evaluating the entire lung parenchyma and should include the entire lungs in the field of view, but expiratory imaging can be limited to the airways. Helical scanning is performed in the craniocaudal direction for both end inspiratory and dynamic expiratory scans. Intravenous contrast material is typically not needed, unless a mass that may be causing extrinsic compression is suspected. Our institutional protocol is provided in Table 2.

MRI Protocol

Cine MRI is a radiation-free alternative to multi-detector CT that allows assessment of the central airway dynamics with the use of a series of breathing maneuvers (30). As they are with dynamic CT, all maneuvers should be performed after active respiratory coaching by an MRI technologist. Given the lack of radiation, an MRI protocol can include more respiratory maneuvers than CT (eg, forced vital capacity [Movie 1], tidal breathing [Movie 2], and hyperventilation [Movie 3]) (31). Disadvantages to MRI include its lower spatial resolution,

limited availability, and longer examination times. Overall acquisition time per patient including localizers, adjustments, breathing instructions, and executing all sequences can reach approximately 25–30 minutes (31). For this reason, few limited studies have been published on the use of MRI in this population.

A brief summary of a suggested MRI protocol involves obtaining three-dimensional static images at total lung capacity and residual volume with a 3D radiofrequency spoiled gradient-echo sequence (repetition time/echo time, 1.4/0.6; flip angle, 2°; sagittal volume acquisition, with true isotropic $3.0 \times 3.0 \times 3.0$ mm³ voxels) that covers the entire chest at end inspiration and end expiration. 3D cine MRI is performed with the same imaging parameters and voxel resolution but covering only the trachea and main bronchi (12 cm, sagittal plane). This acquisition is used to measure airway dimensions in pseudo-real time to detect ECAC during dynamic maneuvers. A temporal resolution of 400 msec per volume (48 volumes collected in 19 seconds) can be achieved with the time-resolved imaging of contrast kinetics (TRICKS) view-sharing imaging method, with accelerated imaging options (30).

Assessment of Tracheal Collapsibility

The cross-sectional area of the airway lumen should be measured on end inspiratory and dynamic expiratory CT images by tracing the inner wall of the airway with an electronic tracing tool or using an advanced workstation. These paired measurements should be used to calculate the percentage of collapsibility of the trachea (23,28) with the following equation (Fig 5):

$$LC = 100 \cdot (1 - [LA_e/LA_i])$$

where LC is the percentage of luminal collapse, LA_e is luminal area during dynamic expiration, and LA_i is luminal area at end inspiration.

Table 2: Dynamic CT Protocol for Evaluation of ECAC

Parameter	Sequences*	
	End Inspiratory [†]	Dynamic Expiration [‡]
Patient position	Supine	Supine
Scanning direction	Craniocaudal, typically including the entire chest in the field of view	Craniocaudal, beginning 7 cm below the carina and ending 1 cm above the epiglottis
Scan type	Helical	Helical
Gantry rotation time (sec)	0.5	0.5
Detector coverage (mm)	40	40
Section thickness (mm)	0.625	0.625
Interval (mm)	0.625	0.625
Pitch	1.375	1.375
Voltage (kVp)	120	120
Amperage (mA)	170	40
Dynamic field of view (cm)	22	22
Algorithm	Standard	Standard
Window width/level	500/50	500/50
Scan time (sec)	5	5

Note.—Multidetector CT is performed with a 16-detector-row or higher scanner.

* In addition to the sequences here, an anteroposterior and lateral scout sequence is performed to determine the area of coverage.

[†] Imaging during suspended end inspiration.

[‡] After a few normal breaths, the patient is instructed to take a deep breath and exhale without performing the Valsalva maneuver or pursing their lips. CT acquisition is coordinated to begin with the onset of the patient's forced expiratory effort.

At CT, all measurements should be taken with lung-window settings rather than soft-tissue window display settings to better define the interface between the airway lumen and airway wall (32). There is no clear consensus on the exact location of measurement, although experts recommend measuring the area at standard levels for reproducibility. These locations include 1 cm above the aortic arch and 1 cm above the carina (23,28). In addition, it is helpful to ensure that the site of maximal narrowing is included when collapsibility is calculated.

Physiologically, there is mild narrowing of the airways on expiration. Hence, differentiating normal expiratory narrowing from pathologic narrowing is important. In adults, a threshold of greater than 50% collapsibility was initially proposed in the bronchoscopic literature, although it was later realized that a significant proportion (78%) of healthy individuals exhibit a greater than 50% decrease in cross-sectional airway at dynamic expiratory imaging (23). On the basis of a study (23) of 51 healthy volunteers, greater than 70% is considered a reasonable threshold for establishing a diagnosis of ECAC in adults. The mean \pm SD collapsibility of the upper trachea in this study was 54.34% \pm 18.6, so the proposed threshold is roughly 1 SD

higher than the mean. The severity of expiratory collapse is graded as mild (70%–80%), moderate (81%–90%), or severe (>90%), with definitive treatment typically reserved for narrowing of greater than 90% (26).

In children, a threshold of 50% is typically used for diagnosis (19). Also, as previously mentioned, children often require end expiratory imaging, which may elicit a lower percentage of collapsibility than that found at forceful dynamic expiratory imaging in older children and adults. Thus, a lower threshold should be used for end expiratory imaging than that for dynamic expiratory imaging, although the precise threshold is difficult to determine, because normative data for expiratory collapse in the pediatric population is lacking.

Assessment of Tracheal Morphologic Characteristics in TBM

In addition to tracheal collapsibility that is assessed on dynamic expiratory images, the diagnosis of TBM can also be suggested on careful review of tracheal morphology on standard chest CT or inspiratory images. The cartilage softening in TBM alters the normal tracheal index (ratio of coronal to sagittal diameter, with a normal ratio of approximately 1). A lunate shape results from the

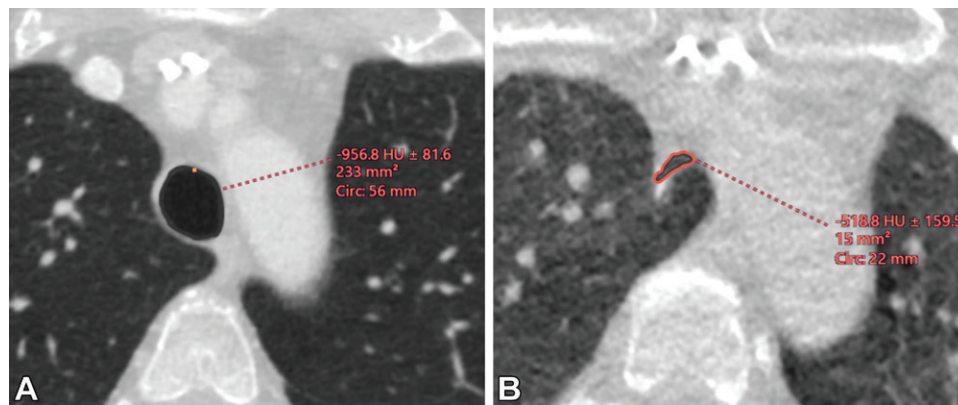


Figure 5. EDAC in a 61-year-old woman. (A) Axial end inspiratory thin-section CT image shows contouring of the inner wall of the airway (border of the black circular area; luminal area [LA], 233 mm²). (B) Axial end expiratory thin-section CT image shows contouring of the inner wall of the airway (red tracing; luminal area [LA_e], 15 mm²). The percentage of luminal collapsibility (LC) is calculated with the following equation: $LC = 100 \cdot (1 - [LA_e/LA_i]) = 94\%$.

weakness of the anterior cartilage (Fig 6), leading to an increase in the tracheal index, while a saber-sheath trachea, with a narrow transverse diameter, results from lateral cartilage malacia (Fig 2D), leading to a decrease in the tracheal index (typically to two-thirds or less of the normal index). Although the tracheal index can be calculated, in routine practice it is often evident on subjective assessment. Various 3D postprocessing techniques can be used to generate two-dimensional multiplanar reformatted thin-section multidetector CT images and external and internal 3D renderings of the airways (Fig 7) (33). Although 3D images may not be necessary for diagnosis, they can represent the craniocaudal extent of the involvement of the luminal narrowing. Internal 3D rendering or virtual bronchoscopy can help in the evaluation of the internal lumen and provides a view similar to that of conventional bronchoscopy (20) and can help clinicians to plan biopsies with a trans-bronchial approach, assess the extent of luminal compromise, and visualize intrinsic abnormalities such as an endobronchial mass that may cause stenosis (34,35).

Air Trapping and ECAC

Expiratory air trapping is commonly encountered in patients with ECAC and is multifactorial. The common association of ECAC with diseases such as asthma and COPD is an important factor (Fig 3). As discussed previously, small-airway diseases may predispose an individual to EDAC because of respiratory dynamics. However, some authors (36) also suggest that ECAC could lead to air trapping by various mechanisms such as chronic inflammation of small airways from impaired airway clearance in patients with ECAC. Because air trapping has also been shown in infants, for whom this long-standing mechanism of small-airway disease

may not be applicable, a component of expiratory collapsibility affecting the peripheral small airways is also possible. The pathophysiologic mechanisms are unclear at this time, and larger future studies could help to address this question. In a study, Zhang et al (37) showed that 100% ($n = 10$) of patients with ECAC exhibited air trapping, compared with 60% (six of 10) of control subjects. These studies are limited by small sample size and qualitative estimation of the severity of air trapping. Several different patterns of air trapping have been described, including lobular, segmental, lobar, and diffuse air trapping, although lobular air trapping is the most frequently observed pattern (50%; $n =$ five of 10 patients) (37). In addition, the degree of air trapping has been reported to be more severe in patients with ECAC than in control subjects (37).

Challenges and Opportunities in Imaging Diagnosis

Given the overlap in symptoms of ECAC with symptoms of other comorbidities, imaging is usually performed for other reasons, hence subjecting the radiologist to framing bias. Furthermore, the trachea is usually considered a blind spot. It is important for imagers to have a high index of suspicion and to understand the imaging appearance of this underdiagnosed condition. CT examinations for pulmonary embolism can allow incidental diagnosis of ECAC, because they are typically performed during expiration to improve contrast opacification of the pulmonary arteries. In addition, these patients are often dyspneic, and the scan may be inadvertently obtained during dynamic expiration. Approximately 10% of patients have been found to exhibit imaging features of tracheal or bronchial collapsibility on CT images acquired to evaluate for pulmonary embolism, al-

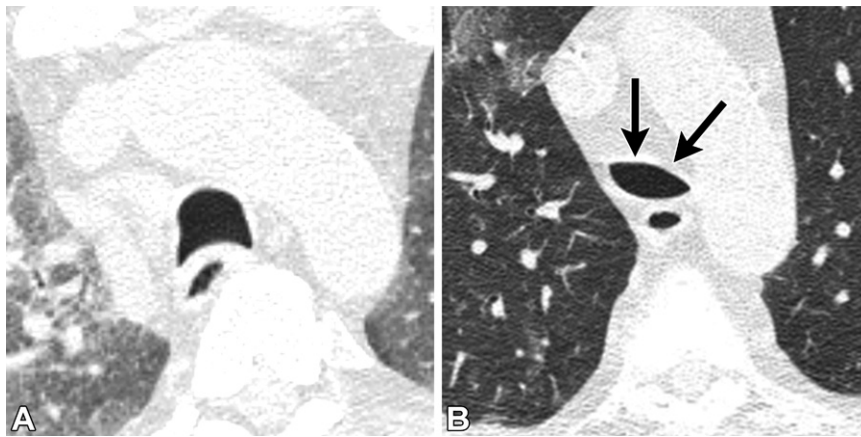


Figure 6. Tracheal index and morphology. (A) Axial CT image in a 76-year-old man shows the normal tracheal morphology, with a tracheal index of approximately 1. (B) Axial CT image in a 67-year-old man shows a lunate trachea resulting from abnormal anterior softening of cartilage (arrows). The tracheal index is increased because of an increase in the coronal dimension relative to the sagittal dimension.



Figure 7. EDAC in a 61-year-old woman. (A) 3D volume-rendered inspiratory CT image shows normal luminal caliber on inspiration. (B) Expiratory 3D volume-rendered CT image shows corresponding luminal collapse (EDAC; arrow). 3D images allow appreciation of the craniocaudal extent of the abnormality.



Figure 8. EDAC in a 78-year-old woman who presented with shortness of breath and underwent CT for evaluation of a possible pulmonary embolism. Axial chest CT image (mediastinal window) shows tracheal collapse with the frown sign, which was missed on this partial expiratory scan. The patient presented 2 days later with stridor and received a diagnosis of EDAC. Radiologists must be vigilant to recognize this underdiagnosed condition.

though the diagnostic threshold used in the study (38) was 50% luminal collapse (Fig 8). When the diagnosis of ECAC is suggested, correlation with clinical symptoms and comorbidities is recommended to determine the treatment strategy.

Management Strategies

Treatment may be indicated for patients with EDAC and TBM, depending on the severity of symptoms and the effect of the disease on quality of life, as summarized in the flowchart (Fig 9).

Asymptomatic Individuals

In asymptomatic individuals with findings of ECAC, no further workup is needed (23). Hence, when the diagnosis is suggested at imaging, clinical correlation with symptoms and comorbid conditions is important.

Symptomatic Individuals

Medical Management.—In most cases, initial treatment of ECAC is medical and focused primarily on treating underlying comorbid conditions such as pulmonary diseases (eg, COPD, asthma, or infections), obesity, gastroesophageal reflux, and sleep apnea (22,39,40).

Patients frequently express concern that they are unable to expectorate secretions, leading to severe episodes of cough or recurrent pneumonia. Strategies to facilitate expectoration of mucus should include the use of mucolytics, bronchodilators (administered by means of nebulization), and adjunct use of airway clearance devices such as flutter valves or external high-frequency vest oscillation of the chest wall. Nebulized β -agonists have a major role because they produce bronchodilation

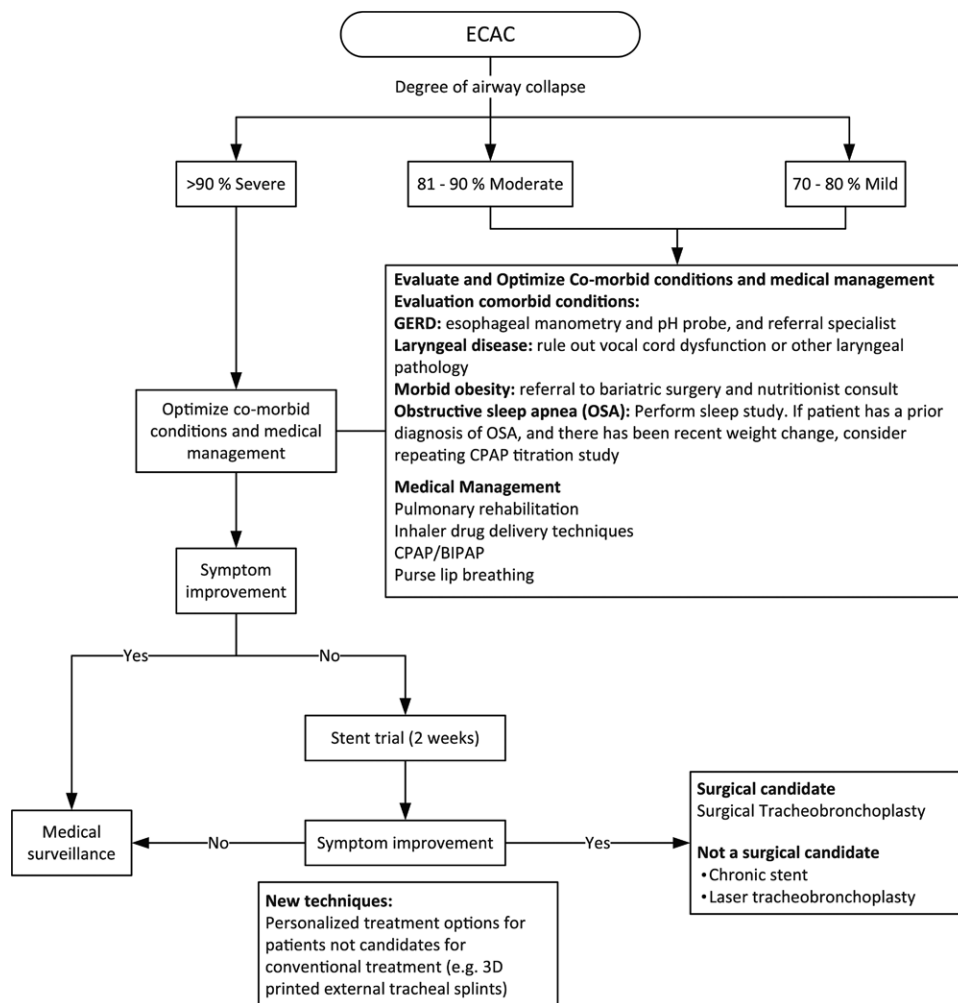


Figure 9. Flowchart shows step-by-step approach to management of ECAC (2). BIPAP = bilevel positive airway pressure, CPAP = continuous positive airway pressure, GERD = gastroesophageal reflux disease.

of small airways, which is a major component of flow limitation, and enhance mucociliary clearance by increasing the frequency of the ciliary beating in the airway cells (41).

The creation of a “pneumatic splint” is another strategy to decrease the expiratory luminal collapse of major airways, which can be achieved by breathing with pursed lips, using proper respiratory techniques, and/or applying continuous positive airway pressure (42,43). Enrollment of the patient in pulmonary rehabilitation to increase cardio-pulmonary performance and provide instruction on proper respiratory technique is often helpful. Similarly, evaluation and treatment of obstructive sleep apnea can often mitigate the adverse symptoms that affect the patient’s quality of life.

Invasive treatment of TBM and EDAC should be reserved only for symptomatic patients with severe disease (>90% collapse) for whom maximal medical therapy has been unsuccessful (2) because of the risks, cost, and limited data on the efficacy of endoscopic and surgical interventions.

Stent Trial.—A 2-week stent trial should be considered before performance of surgical tracheobronchoplasty (TBP) to ensure appropriate patient selection for the procedure. Only patients who demonstrate both symptomatic and objective improvement during the stent trial should undergo surgery.

Both the patient and the medical team should understand that although patient symptoms may improve, the stent is temporary and is part of the workup that will help to identify those who will benefit from surgical TBP (2,44) (Fig 10). Studies (2,45,46) have reported that 60%–75% of patients exhibit improvement in symptoms after the stent trial and undergo surgical TBP. Approximately 80% of these patients demonstrate improvement in quality of life, exercise tolerance, and symptoms after undergoing definitive surgical treatment.

Silicone Y stents placed under rigid bronchoscopy were initially used for patients with TBM and EDAC. Although studies (47,48) showed improvement in symptoms, quality of life, and functional status with silicone stents, the high complication

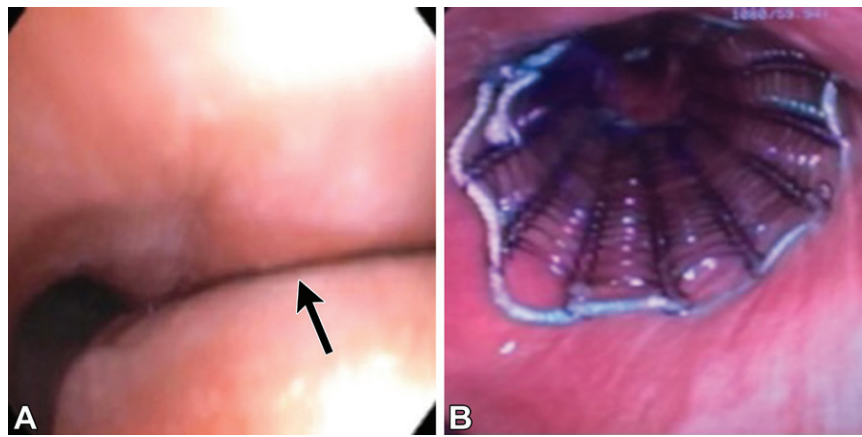


Figure 10. Stent trial for EDAC. (A) Dynamic bronchoscopic image shows severe collapsibility of the airway at the level of the right main stem bronchus (arrow) and the trachea (not shown). (B) Rigid bronchoscopic image shows an uncovered self-expanding metallic stent that was placed for 2 weeks in the right main stem (shown) and the trachea (not shown). (Case courtesy of Eugene Shostak, MD; Weill Cornell New York Presbyterian Hospital.)

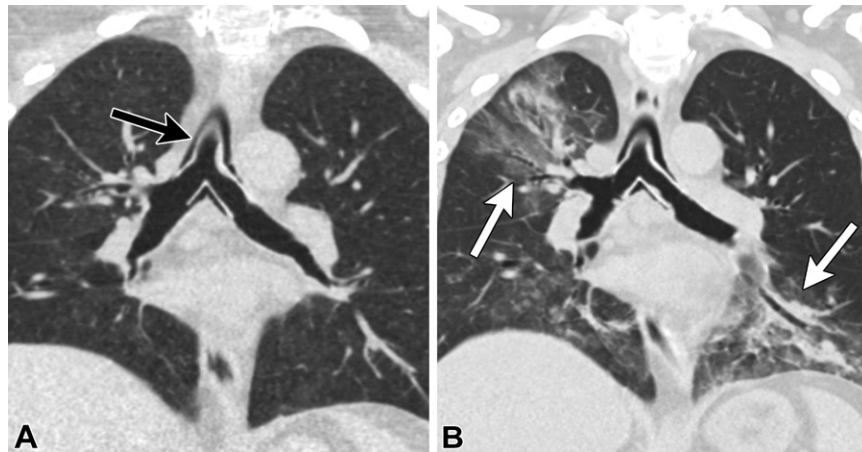


Figure 11. Stent complication in a 47-year-old woman with a history of asthma, sleep apnea, and TBM who was not a candidate for surgery because of comorbidities and was treated with placement of a long-term stent. (A) Coronal chest CT image (lung window) acquired 4 months after stent placement shows the normal appearance of the stent (arrow). (B) Coronal CT image (lung window) acquired 9 months after stent placement shows patchy air-space opacities, with mucus plugging suggestive of infection (arrows). The patient underwent removal of the stent, with recurrence of TBM.

rates, the need for repeat bronchoscopy to maintain stent patency, and the scarcity of long-term data are arguments against long-term use of silicone stents (49). Currently, uncovered self-expanding metallic stents are commonly used during stent trials in patients with TBM and EDAC (2,44,50). The major benefit of these uncovered metallic stents is the potential for decreased mucus plugging. However, the risk of excessive granulation tissue and the higher cost of self-expanding metallic stents are factors that should be considered before their deployment.

To minimize complications, we suggest careful evaluation and precise measurement of airways with both CT and bronchoscopic techniques, regardless of the type of stent used, to help in selecting the proper stent size and configuration.

In selected cases, long-term stents may be used in patients who are poor candidates for surgery. Tracheal and bronchial stents can lead to complications including but not limited to stent obstruction due to plugging with mucus and/or granulation tissue, migration and fracture of the stent, bacterial infection, perforation of the airway, and hemoptysis in patients with nonmalignant airway disease, for which imaging evaluation can be performed, as needed (47,49–55) (Fig 11).

Surgical Treatments.—Surgical treatment options include tracheal resection, tracheostomy, and TBP. Tracheal resection is reserved for the focal short segment of tracheomalacia and is rarely performed, because TBM often involves a substantial segment of the airway (21). Creation of the tracheostomy allows the tracheostomy tube to act as an intraluminal stent, maintaining airway patency by preventing airway collapse. However, tracheostomy negatively affects the quality of life of the patient and does not adequately address bronchomalacia.

TBP is considered for patients with EDAC who are good candidates for surgery, have received optimal medical treatment, and have substantial improvement in symptoms after a stent trial. The goal of surgical treatment is to reinforce and stabilize the posterior membranous portion of the airway including the trachea, the right and left main stem bronchi, and the bronchus intermedius (46). Patients are often best served when they undergo surgery at a large medical center in which these procedures are performed regularly.

The procedure is performed by means of a right thoracotomy, which allows exposure of the entire airway including the left main stem. Once the airway is exposed, the posterior wall of the trachea

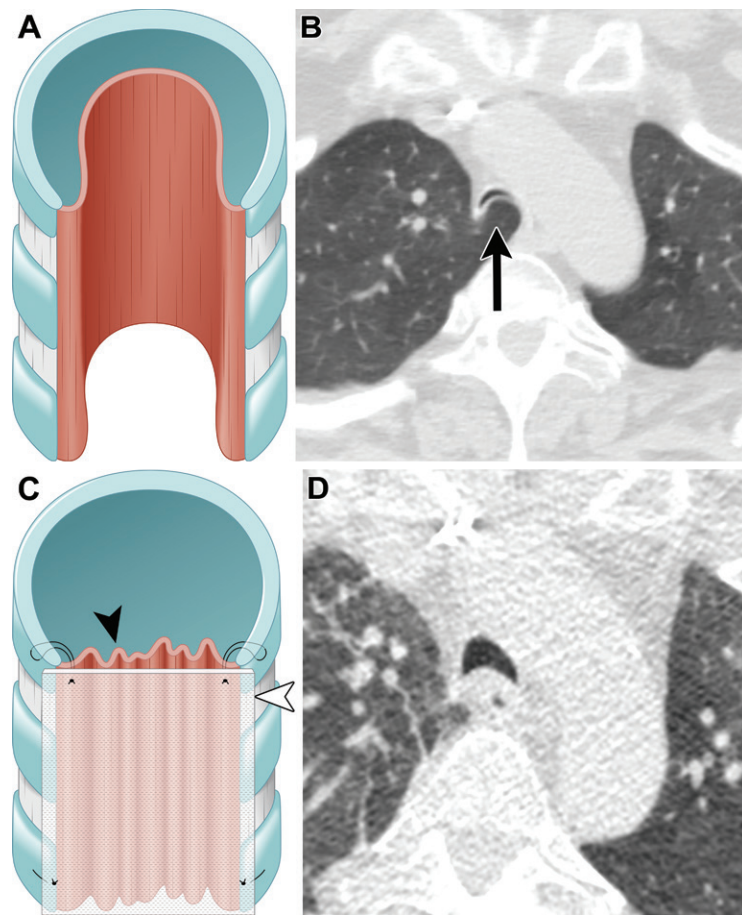


Figure 12. EDAC in a 61-year-old woman who underwent tracheobronchoplasty (TBP). (A, B) Illustration (A) and axial preoperative chest CT image (B) show the dynamic airway collapse of the mid trachea (arrow in B). (C) Illustration shows the appearance of the trachea after TBP. Note the plication of the posterior membrane wall (black arrowhead) with absorbable polypropylene mesh (white arrowhead). (D) Postoperative axial thin-section CT image acquired during expiration shows an improvement in expiratory collapse.

is plicated by placing an absorbable mesh, which is then fixed in place with several rows of absorbable sutures, along the membranous portion of the airway (56) (Fig 12). This procedure is repeated for the right main stem, the bronchus intermedius, and the left main stem airways. The mesh splint should be measured carefully to ensure that it is properly sized. In addition, the surgeon must ensure that the mesh is taut for proper stabilization of the posterior membrane. Hence, knowledge of tracheal configuration and the difference between the appearance of EDAC and that of TBM at preoperative imaging can be helpful. Patients with TBM often have a larger transverse tracheal diameter that requires lateral downsizing than that in patients with EDAC (3). When TBP is completed, flexible bronchoscopy is performed to evaluate the resultant anatomy. Patients should be monitored in an intensive care or step-down unit; aggressive pulmonary hygiene should be instituted postoperatively, with incentive spirometry, flutter valve therapy, and early patient ambulation. Postoperative complications occur in up to 47% of patients and include respiratory tract and wound infections, acute kidney injury, pleural effusions, pneumothorax, and atrial arrhythmia (57).

Surgical correction of TBM or EDAC in well-selected patients results in substantial improve-

ment in respiratory quality of life, dyspnea indices, performance status, and exercise tolerance, as reported by Buitrago et al (57). In a study of 14 patients, Wright et al (58) also demonstrated improvement in forced expiratory volume at 1 second, forced vital capacity, and peak expiratory flow rates. Advancement in surgical techniques has allowed the performance of robotic TBP. A study (59) of 42 patients who underwent robotic TBP showed significant improvement in pulmonary function test results and high overall patient satisfaction.

After surgical treatment, the airway is routinely further assessed with dynamic CT studies, which are compared with preoperative studies to determine the degree of improvement in airway collapse (60) (Fig 12). Baroni et al (60) reported a decrease in airway collapse on expiratory CT images and normal airway morphology on inspiratory CT images after tracheoplasty in all five patients studied.

Imaging Surveillance after Surgical Treatment

Currently no standard guidelines exist on the timeline for routine imaging surveillance of patients who have undergone surgical treatment for TBM and EDAC, although imaging is performed for recurrence of clinical symptoms or

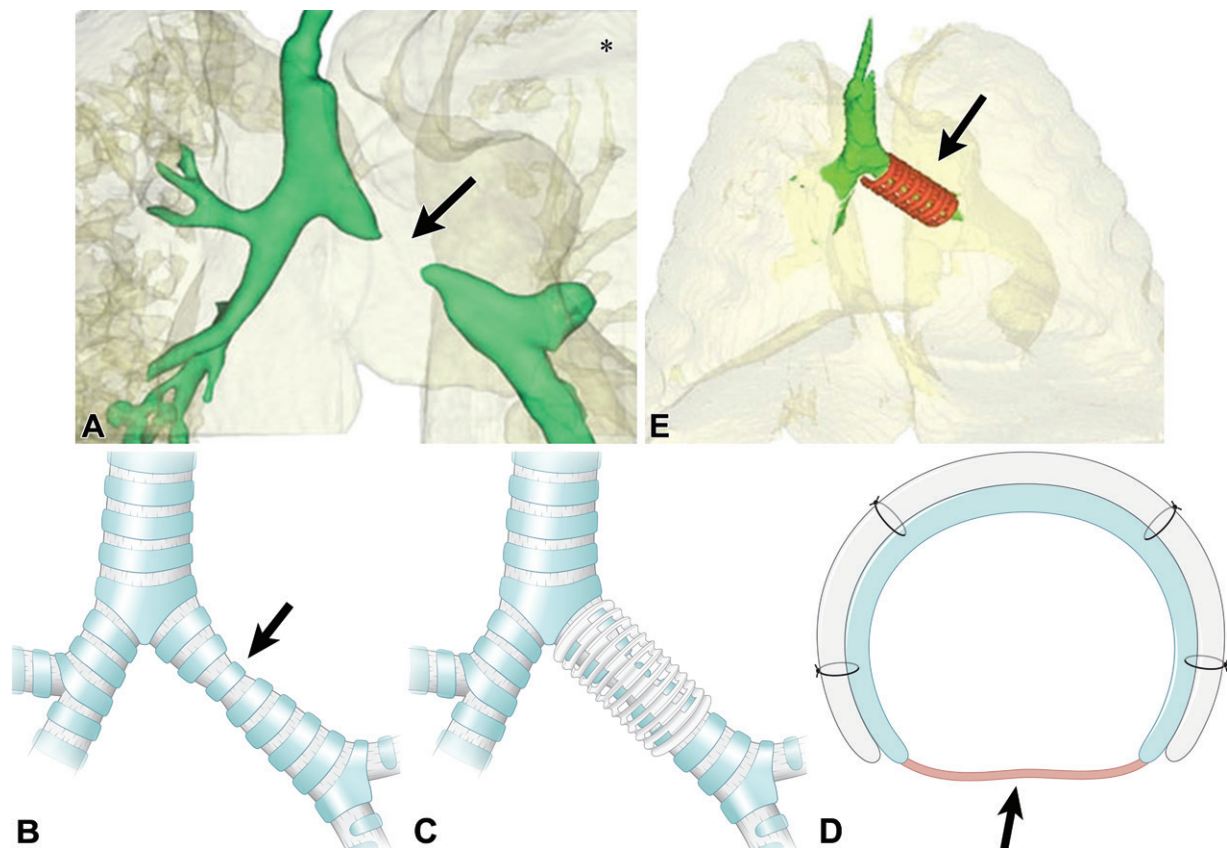


Figure 13. Respiratory failure and left bronchomalacia in a 3-month-old male infant. (A) Airway model created from an expiratory chest CT study with the use of Materialize Mimics software (www.materialise.com/en/medical/mimics-innovation-suite) shows left bronchomalacia (arrow) with expiratory collapse and air trapping in the left lung (*), which appears diffusely hyperlucent relative to the right lung. Challenges in treatment include the size of the infant's airway and future body and tracheal growth, which make a stent impractical. (B–D) Illustrations show preoperative left bronchomalacia (arrow in B) and the postoperative bronchus with a patient-specific bioresorbable custom splint (C, D) that was generated from the CT study and acts as an external scaffold attached to the outer wall of the airway, allowing for radial expansion (arrow in D). (E) Postoperative airway model derived from expiratory chest CT images shows the splint positioned in the left main stem bronchus (arrow).

complications. Bezuidenhout et al (24) evaluated intermediate (approximately 1.5 years) and long-term (approximately 6 years) changes in expiratory tracheal collapsibility in patients with TBM after surgical treatment with dynamic CT. They showed a significant decrease in expiratory tracheal collapsibility, from a mean \pm SD of $72\% \pm 25\%$ at baseline to $37\% \pm 21\%$ at intermediate follow-up ($P < .001$). Collapsibility increased to $51\% \pm 20\%$ in the upper trachea at long-term follow-up, which was substantially worse than that at intermediate follow-up ($P = .002$) (60) but still remained significantly lower than preoperative collapsibility ($P = .015$). These findings suggest the importance of quantitative measurement at dynamic CT for evaluation of the response to TBP (24).

New Advances in Treatment

Laser TBP

Laser TBP is an emerging endoscopic technique for patients with severe ECAC who remain symptomatic despite maximal medical therapy

but are not candidates for surgical TBP. Laser activation in the posterior wall of the right and left main bronchi, the bronchus intermedius, and the trachea induces fibrosis of the area (61,62), thus decreasing the degree of dynamic airway collapse. Laser settings, the type of laser (eg, yttrium aluminum garnet vs holmium), and the number of sessions differ according to the institution (39,63). The long-term benefits of laser therapy in patients with ECAC are currently unknown.

3D-printed Tracheal Splints

Despite conventional treatments, a subset of patients with severe ECAC experience continued morbidity. Given that TBM is a structural disease that can affect multiple segments of the airway, it is well suited to the use of patient-specific medical devices. A bioresorbable 3D-printed tracheobronchial splint that is externally implanted for tracheobronchial suspension was first developed at the University of Michigan (Ann Arbor) for infantile TBM (64) (Fig 13). With this treatment approach, a segmented CT study to generate a 3D model of the

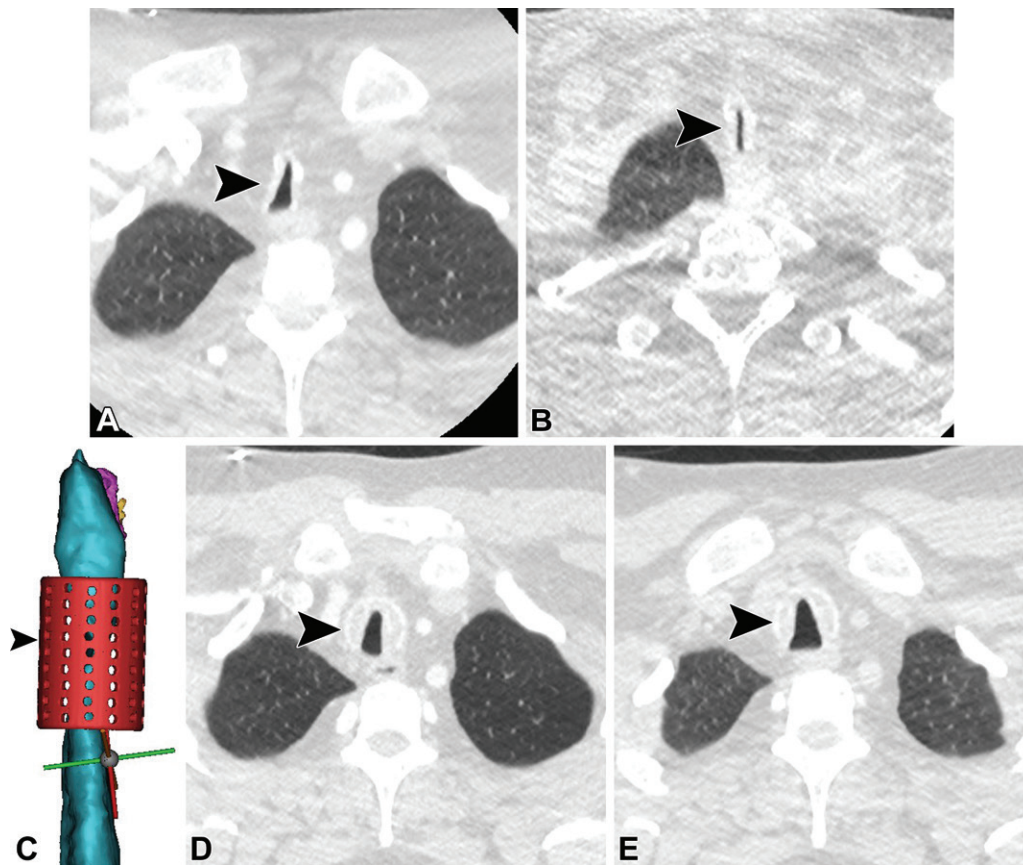


Figure 14. Long-standing tracheostomy leading to fixed tracheal stenosis and TBM in a 46-year-old man. (A) Axial inspiratory chest CT image (lung window) shows tracheal stenosis just below the thoracic inlet (arrowhead). (B) Axial expiratory phase CT image shows concomitant severe saber-sheath tracheomalacia with collapsibility of the lateral walls (arrowhead). (C–E) Illustration (C) and axial inspiratory (D) and expiratory (E) chest CT images show a 3D-printed polyetherketoneketone external tracheal splint (arrowhead) at the site of tracheal stenosis with mild persistent, although improved, stenosis. Note the substantial improvement in tracheomalacia during expiratory phase imaging (E).

patient's airway, and computer-aided design is used to measure and model an external tracheal splint to fit the affected TBM segment. The archetypal design of the device is an open-bellowed cylinder with 10 design variables to allow the best fit (65). The device is then manufactured from polycaprolactone, which is a biocompatible and bioresorbable polyester, with a selective laser-sintering 3D printer and remains in the patient for 2–3 years before resorption (65). The device is placed after external exposure of the malacic airway segment, suspending the walls of the airway to the framework of the device through designed suture holes (66). The design and manufacturing approach allow a high degree of customization and adaptability to the patient's airway defect. Typically, the time frame from evaluation of patient candidacy to production of the device, which encompasses imaging, computer-aided design, and 3D laser sintering manufacture, is less than 5 days (66).

This approach was used successfully in 15 pediatric patients with severe refractory TBM (67) and was reproduced at another institution with a

polycaprolactone splint for an adult patient with TBM (68). The same design process was used to create a 3D-printed external tracheal splint made of a permanent biopolymer (polyetherketoneketone, which may provide a more durable solution for adult phenotype TBM) for an adolescent with acquired tracheomalacia (69) (Fig 14). To date, 3D-printed external airway splints have been used in a humanitarian setting under regulatory exemption for patients who were not candidates for or who were unsuccessfully treated with conventional therapies (70).

Conclusion

TBM and EDAC remain challenging diagnoses that share symptoms with other comorbid conditions. Evolution in CT technology and increased use of advanced postprocessing techniques have enabled better assessment of the airway. With the advent of new treatment options, dynamic CT not only is important in diagnosis, but also provides a guide map for surgical planning and is being used for treatment options including

patient-specific 3D-printed splints. However, further experience in longitudinal clinical trials and federal regulatory approval is necessary to determine the best criteria for patient selection before external airway splinting can be introduced into standard practice.

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