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REVIEW ARTICLE

Tracheobronchomalacia and excessive dynamic airway collapse

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Abstract: Tracheobronchomalacia and excessive dynamic airway collapse are two separate forms of dynamic central airway obstruction that may or may not coexist. These entities are increasingly recognized as asthma and COPD imitators. The understanding of these disease processes, however, has been compromised over the years because of uncertainties regarding their definitions, pathogenesis and aetiology. To date, there is no standardized classification, diagnosis or management algorithm. In this article we comprehensively review the aetiology, morphopathology, physiology, diagnosis and treatment of these entities.

Key words: airflow dynamics, bronchomalacia, excessive dynamic airway collapse, tracheobronchomalacia, tracheomalacia.

INTRODUCTION

The purpose of this systematic review is to clarify confounding issues pertaining to the definition, pathophysiology, histopathology, aetiology, diagnosis, classification and treatment of acquired and idiopathic forms of adult tracheobronchomalacia (TBM) and excessive dynamic airway collapse (EDAC). Based on a thorough review of existing English language literature since the mid-1960s, we submit that TBM, although characterized by weakness of airway cartilage, may occur either with or without an excessive dynamic invagination of the posterior membranous portion of the tracheobronchial tree. This latter process, referred to as EDAC, appears to be a distinct clinicopathologic entity which may or may not result from hypotonia of myoelastic elements of the posterior membrane. We submit that TBM and EDAC can occur independently from each other or together, and may be part of the same pathological process or result from very different mechanisms.

Understanding the distinctions between these two entities has been challenging for several reasons. The first is that most published studies are case series and retrospective descriptions, many of which report a single investigator's experience with diagnosis and management. In fact, it is puzzling that despite the relative frequency with which TBM and EDAC are presumably encountered, multi-institutional or prospective studies have not been published. The second is that investigators rarely define and differentiate TBM and EDAC as two separate entities, often using words such as malacia and collapse interchangeably, describing EDAC findings while calling it TBM or vice-versa. Recently available radiographic and bronchoscopic imaging techniques however, enhance the clinician's ability to differentiate these two processes. A third issue is the absence of a universally accepted nomenclature and classification. Indeed, few investigators classify TBM or EDAC using more than one radiographic, bronchoscopic, or histopathologic criterion.

METHODS

All published literature pertaining to acquired or idiopathic TBM was collected by searching PubMed (MEDLINE) from the mid-1960s to April 2005 using the following key words: *tracheomalacia, bronchomalacia, tracheobronchomalacia, adult, acquired, dynamic airway collapse, choke point, tracheal collapse, bronchial collapse and tracheobronchial collapse*. We also performed specific disease searches for *relapsing polychondritis, congenital tracheobron-*

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chomegaly and *thyroid disease* because these conditions are known to be associated with TBM. Abstracts and case reports were included. When articles were published in a foreign language, however, only the English language abstracts were reviewed. Searches were augmented by manually reviewing the reference lists of all original research and all review articles. Because the purpose of this systematic review was neither to perform a meta-analysis nor to grade the evidence of the published literature, this methodology is limited but not flawed by the fact that only a single database for locating articles was used and that other electronic databases such as EMBASE, LILACS or Best Evidence were excluded.

DEFINITIONS

Tracheobronchomalacia

The term malacia derives from the Greek word 'malakia', which means softness. TBM has been defined as a condition in which there is weakness of the tracheal and bronchial walls due to softening of the supporting cartilage and hypotonia of myoelastic elements.[1,2] As a result, the trachea and main bronchi lose their usual degree of stiffness and the airway walls come closer together. This results in a reduction of airway lumen and causes a disease state encompassing intermittent or continuous dyspnoea, difficulty clearing secretions, cough, wheezing, recurrent bronchitis or pneumonia that has traditionally been called TBM.

Excessive dynamic airway collapse

TBM is also referred to in the literature, however, as tracheobronchial collapse,[3,4] expiratory tracheobronchial collapse, expiratory tracheobronchial stenosis,[2] tracheobronchial dyskinesia,[5] or described as dynamic airway collapse (DAC).[1,6–9] This contributes to some confusion regarding these distinct entities. Dynamic CT measurements of the normal trachea during forced expiration show a mean decrease of 35% (range 11–61%) in the cross sectional area (CSA) of the trachea between inspiration and expiration. Thus, a certain degree of DAC characterized by invagination of the posterior membrane of the tracheobronchial tree is physiological and probably enhances expectoration and secretion clearance. In healthy individuals, cine-bronchography studies show, in fact, that the tracheobronchial lumen during coughing is 18–39% narrower than the maximal inspiratory lumen observed during restful respiration.[10] DAC is exaggerated, however, in some patients with obstructive pulmonary disease such as chronic bronchitis, emphysema, asthma and TBM. Excessive collapse may also be seen as an isolated finding in patients during cough and forced expiration. A reduction of airway lumen by 50% or more in the sagittal diameter has been considered abnormal[4,11] and, when due to invagination of the posterior membrane, should probably be referred to as EDAC[6–8] (Fig. 1).

Distinguishing TBM from EDAC

In the literature, there is no clear distinction between EDAC and TBM. In fact, defining TBM as a narrowing of the lumen by 50% or more while coughing as documented by fluoroscopic observations[11] or by bronchoscopy[12] may give rise to a missed diagnosis of EDAC and to false positive cases of TBM in the absence of cartilaginous involvement. In one frequently quoted review article, the term TBM is used interchangeably to describe EDAC and malacia.[1] EDAC has been also referred to as TBM in several reports using bronchoscopy for diagnosis.[2,12–14] In the radiology literature, TBM has also been classically defined as a reduction in airway CSA greater than 50% on expiratory images.[6–8] It appears that prior investigators have often used the term TBM while referring to EDAC and vice versa.[6–9]

Morphologies of TBM and EDAC (Fig. 1)

The radiology and bronchoscopy literature refer to several morphological types of TBM.[1,2,7,9,12–17] The crescent or membranous type is due to an apparent weakness of the membranous part of the airway and felt to represent an atrophy of the longitudinal elastic fibres of the posterior wall.[1,2,7,9,12–14] The cartilaginous type of TBM is caused by a weakness of the lateral and anterior cartilaginous walls of the airways.[7,15–17] This type can have a crescent or saber-sheath appearance on bronchoscopic or radiographic examination depending on whether the anterior or lateral walls of the airway are weakened. This is a dynamic process and is different from saber-sheath trachea which is a fixed narrowing described in up to 5% of older males with COPD.[18–20] A combined or circumferential type refers to a combination of crescent and saber-sheath type[16] or when a disease state, such as polychondritis, results in circumferential narrowing of the airway lumen.[21]

PREVALENCE

The reported prevalence of TBM and EDAC varies with the study population, the diagnostic methodologies employed, and the criteria used to define airway collapse. Previous investigators often referred to TBM as a narrowing of the anteroposterior diameter of the airways without specifying whether collapse was secondary to a cartilaginous process.[2,11,13,22] This describes a crescent-type abnormality, forcing the reader to presume that saber-type malacia was not noted. In many of these papers, EDAC is described but not identified as such.[1,6–9]

In one study, expiratory collapse of the trachea and main bronchi was noted to be greater than 50% during cough. This was seen during bronchoscopy in 11 of 78 patients (14.1%) referred to a pulmonologist for evaluation of chronic cough lasting an average of 72 months.[23] This is a frequently quoted paper regarding incidence of TBM.[6–8] This article, however, describes EDAC and does not mention abnormali-

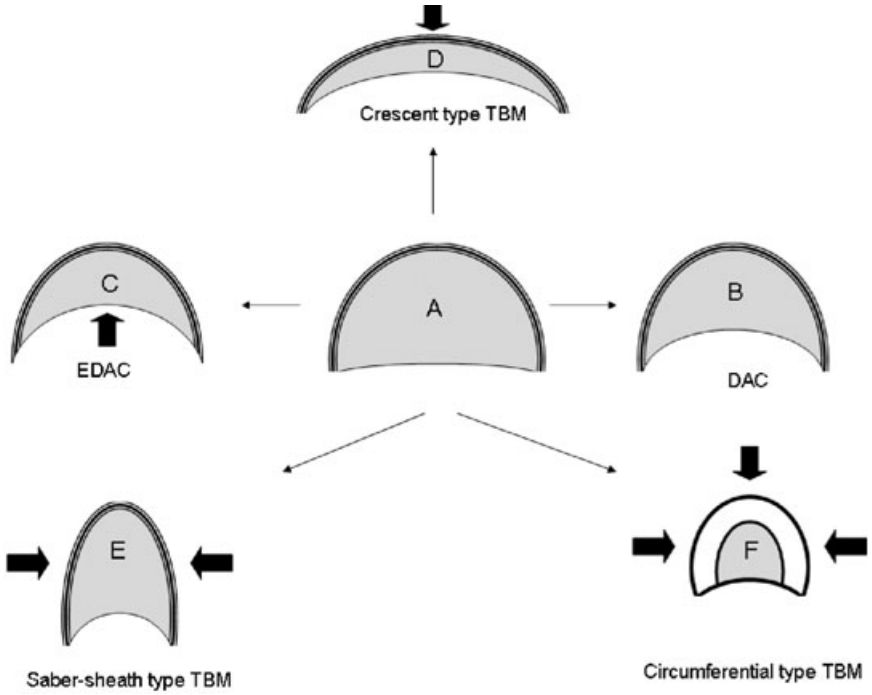

Figure 1 Airway lumen during inspiration (A). During expiration there is inward bulging of the posterior membrane. This process is physiological and is called dynamic airway collapse (DAC) (B). The pathologic exaggeration of this process results in a reduction in cross sectional area of 50% or more and is called excessive dynamic airway collapse (EDAC) (C). The pathological collapse of the cartilaginous rings represents tracheobronchomalacia (TBM). The crescent type TBM occurs when the anterior cartilaginous wall is softened and results in excessive narrowing of the sagittal airway diameter (D).The saber-sheath type TBM is due to softening of the lateral walls and excessive narrowing of the transverse airway diameter (E). Circumferential (combined) type TBM is characterized by anterior and lateral airway walls collapse and is usually associated with significant airway wall inflammation (F).

ties of the cartilaginous walls. In a large retrospective report, acquired TBM was identified bronchoscopically in 94 of 2150 patients (4.5%).[13] TBM was of the crescent type only, but the authors did not specify whether softening of cartilage was noted. TBM was also noted in 50 out of 214 patients (23%) with chronic bronchitis who underwent bronchoscopic evaluation.[14] Similar uncertainties regarding definition and nomenclature mentioned previously limit the interpretation of findings in this study.

In 1992, Ikeda *et al*. reported findings of acquired TBM in a large retrospective case series involving more than 4283 patients who underwent videobronchoscopy.[22] The authors classified the degree of severity of TBM into three groups: first degree 0–50% narrowing of the airway calibre, second degree 50–75%; and third degree 75–100% airway narrowing. They reported second and third degree TBM in 542 (12.7%) of all patients; Seventy-two per cent of these patients were between the ages of 50 and 80 years. Third degree TBM was found in 131 patients (3.1%) with a frequency of 2.2% if patients were younger than 50 years and 6.2% for patients older than 80 years. Here also, the prevalence of the crescent and saber-sheath type was not independently reported. The prevalence of saber-sheath type of TBM has been rarely reported and seems to be much less common than the crescent type.[7,16] Gilkeson, for example, identified saber-sheath type in only two out of eight patients with TBM[7] while Taki *et al.* as quoted by Imaizumi[16] states that the incidence of this type of TBM is 5% but does not provide additional references. We have identified only two case reports in the English language literature of combined crescent and saber-sheath type malacia.[16,21] Therefore, the overall incidence of combined abnormalities cannot be quantified.

In summary, we identified only four articles addressing the prevalence of TBM.[13,14,22,23] There were no specific references to EDAC, nor did most authors differentiate dynamic abnormalities of the posterior membrane from abnormalities of the cartilaginous airway walls. From these studies, it appears that either TBM or EDAC is present in approximately 4–23% of patients undergoing bronchoscopy for various indications.

PATHOPHYSIOLOGY

Applied physiology

During inhalation, tracheobronchial lumen normally increases as the relaxed posterior membrane bulges outwards as a result of increased transmural

pressure while pleural pressure becomes increasingly negative. However, smooth muscle contractions oppose exaggerated distension. During exhalation, the posterior membrane bulges inwards, causing narrowing of the tracheobronchial lumen. During forced expiration, tension in the smooth muscle opposes exaggerated invagination of the posterior membrane and stabilizes the airway structure against excessive narrowing.[24,25] In the absence of smooth muscle tone, a negative transmural pressure gradient causes invagination of the posterior wall and airway narrowing. This can result in EDAC. In the malacic intrathoracic airway as well as during coughing, expiratory collapse, whether at the level of the cartilaginous walls or at the level of the posterior membrane, occurs when intrathoracic pressure exceeds intratracheal pressure. In order to enhance clinician's understanding of TBM and EDAC, the basic principles governing expiratory flow limitation will be reviewed.

The 'equal pressure point' (EPP) theory

It is generally understood that intrathoracic airways behave as check valves such that expiratory flow becomes limited at modest positive transpulmonary pressures. Thus, at a given lung volume, expiratory flow no longer increases with driving pressure.[26] In 1967, Mead *et al*. demonstrated that once expiratory flow becomes limited at a given lung volume, there would be a region within the intrathoracic airway where intrabronchial and extrabronchial pressures become equal.[27] This EPP divides the airways into upstream segments (alveolarward from the EPP) at which transmural pressure is positive, and downstream segments (mouthward from the EPP) at which the transmural pressure is positive within the extrathoracic airways and negative within the intrathoracic airways. At a given lung volume, driving pressure upstream from the EPP would be equal to lung elastic recoil, while downstream from the EPP, airways would be compressed during expiration. This region of compression of intraluminal calibre is referred to as a flow-limiting segment or 'choke point'. As lung volume decreases and pleural pressure increases during forced expiration, the EPP migrates upstream, resulting in a lengthening of the increasingly narrow downstream segment. This increases airway resistance and prevents further increases in expiratory airflow, causing the EPP to become fixed when airflow becomes constant.[27] Lung elastic recoil, small airway resistance and airway compliance are three major determinants of the location of the EPP, all of which may also be influenced by smooth muscle tone. Bouhuys and van de Woestijne showed that bronchodilators increase airway wall compliance, suggesting that increased compressibility will cause the EPP to become fixed at a point closer to the thoracic outlet.[28] Thus, the increased length of the upstream segment and the decreased CSA at the EPP offset the advantage gained by increasing the calibre of the upstream airways with respect to maximal expiratory flow.

Wave-speed theory of flow limitation

The wave speed is the speed at which a small disturbance travels in a compliant, fluid-filled tube. In the arteries this is the speed at which the pulse propagates, whereas in the airways it is the speed at which air flows. Analogous to physical laws that govern flow in fluids, Elliot and Dawson demonstrated that 'in tubes with elastic walls, flow limitation occurs when flow velocity equals the speed of propagation of pressure pulse waves at some point within the tubes'.[29] This point, called the choke point, tends to be at a region of minimum area and minimum side pressure within the airway when maximal flow has been reached. The wave-speed theory of expiratory flow limitation implies that maximum expiratory flow is dependent on airway compliance. Increasing large airway compliance increases airway resistance and decreases maximum expiratory flow, which could contribute to the airway obstruction associated with EDAC and TBM because flow velocity reaches the speed of wave propagation at the choke point, which is now located further downstream towards the airway opening.

HISTOPATHOLOGY

Post-mortem information from patients with TBM and EDAC is scarce and usually based on case reports or small case series. It is noteworthy that we identified only five studies in which histopathological findings were presented.[12,13,15,22,30] It is unclear whether histopathological changes such as atrophy of myoelastic elements and cartilage are primary or simply end-products of injury from other illness. In patients with tracheomalacia the tracheal cartilage-to-soft tissue ratio is sometimes as low as 2:1, while normally it is approximately 4.5:1. In patients with EDAC, atrophy of elastic fibres has been described but is not constant.[12,13] Although TBM has traditionally been classified into three histopathological types: the membranous type, the cartilaginous type and the polychondritic type,[15] we question this traditional classification and propose that what is habitually referred to as a membranous type of malacia when no cartilaginous defects are noted is actually EDAC.

EDAC (traditionally referred to as the membranous type of TBM)

Atrophy of the longitudinal elastic fibres in two patients with TBM and severe emphysema has been noticed,[12] but no mention of cartilaginous abnormalities was made. Similarly, Jokinen *et al*.[13] performed an autopsy in only 1 of 94 patients with presumed TBM, noting a significant decrease in the amount of longitudinal elastic fibres of the membranous portion of the trachea compared with normal controls. No cartilaginous abnormalities were reported. In each of these two studies, the membranous portion of the airway was noted to be flaccid and dilated and the tra-

cheobronchial lumen was narrowed in its sagittal diameter.

TBM (traditionally referred to as the cartilaginous type of TBM)

In at least one study, investigators noted fragmentation of tracheal cartilaginous rings and elongation of the membranous portion of the trachea in its transverse distance.[22] Various inflammatory infiltrations (T lymphocytes and HLA-class II-expressing macrophages) were noted on immunohistochemistry of affected cartilage depending on the severity of involvement. In severe malacia, the cartilage had disappeared and was replaced with collagen. Data regarding histology of the crescent shaped, cartilaginous form of TBM are also scarce. Absence of cartilage was also described in an autopsy report from a patient with TBM due to long-term ventilation through uncuffed tracheostomy tubes. Baydur showed the focal absence of the tracheal cartilage with replacement by a predominantly firm tan-grey fibrous tissue.[30]

Polychondritic type

In reality, the polychondritic type is a cartilaginous form of TBM, but with an extensive local and systemic inflammatory component. Tracheobronchial cartilage shows empty lacunae (empty spaces within the cartilage) and a mixed population of inflammatory cells.[31] Heavy inflammatory exudates are often noted to invade the periphery of necrotic cartilaginous tissues.[32,33] An immunological mechanism is likely because this disease is often associated with rheumatic or autoimmune diseases, although only a few patients with relapsing polychondritis (RP) have autoantibodies.[34]

AETIOLOGY

The primary form of TBM is congenital and is usually an isolated finding, but may be associated or secondary to other congenital conditions.[1,35–39] This form is mainly a disease of infancy and is well described in the paediatric literature,[35,36,39–42] It is characterized by recurrent respiratory infections, cough, hypoxia and cyanosis. The natural history is usually one of gradual improvement as the airway lumen increases in diameter and cartilage becomes more rigid as the child ages. Acquired forms of TBM and EDAC are disorders of middle aged and elderly people. Both can be idiopathic or secondary to other disorders.

Indwelling Tracheotomy and endotracheal intubation with inflatable cuffs was suggested by Feist *et al.*[43] to be a common cause of acquired disease. Pressure necrosis, decreased blood supply, infection and friction of tubes on the airway mucosa cause tracheal injuries that usually heal by contraction and result in fibrous stenosis preserving the normal tracheal cartilage.[44] When the injury is transmural or in the presence of high dose steroids, however, scar formation is minimal and there is loss of cartilaginous support with resultant airway wall collapse.[45] These malacic areas are focal and readily seen at the site of the inflatable cuff, at or 1.5 cm below the tracheostomy stoma, or at the point of impingement of the tip of the tracheostomy or endotracheal tube (ETT) on the tracheal wall.[43]

Long-term ventilation has been described as a cause of malacia in infants and young children after duration of positive pressure ventilation of a few weeks to a few months.[46] Baydur describes the development of acquired TBM in adult patients with Duchenne muscular dystrophy after many years of positive-pressure ventilation via a tracheostomy despite the use of uncuffed tracheostomy tubes.[30] It is not clear, however, if the myopathic involvement of the tracheal muscularis also contributed to the dilation and weakness of the wall. Law *et al.*[47] described malacia in 23% of 81 patients with long-term tracheostomies (mean duration, 4.9 months) examined by fibreoptic bronchoscopy prior to decannulation. It is unknown what level of airway pressure and what period of time on a ventilator is necessary for tracheobronchial damage to occur or whether pressure control ventilation might prevent this complication. There are no reports of TBM in patients receiving non-invasive positive pressure ventilation (NIPPV). Research in this field is important because CPAP, in fact can also serve therapeutically as a pneumatic stent.[37,48,49]

Closed chest trauma such as steering wheel injuries may often cause unrecognized tracheal fractures which can result in TBM. The exact mechanism leading to softening of the cartilage is unknown but is likely related to impairment in blood supply. It is noteworthy that malacia can be induced by fracturing tracheal cartilages.[50–52]

Chronic irritation of the airway, as seen in smokers, can cause chronic cough which may weaken the tracheal and bronchial wall. Chronic inflammation and irritation from smoking or air pollution have, in fact, been described as risk factors for TBM.[1,11] Earliest reports[12] considered TBM to be connected with emphysema. Nuutinen, in a clinical study involving 47 patients with TBM, showed that the prevalence of emphysema is essentially the same, however, as in a normal population of similar age.[2]

Chronic airway and soft tissue inflammation appears to cause progressive atrophy and destruction of the tracheal or bronchial cartilages resulting in progressively diffuse TBM. This is most significant in patients with RP.[34,53] The tracheobronchial tree is reportedly involved in about 56% of patients and respiratory symptoms are responsible for the initial presentation in about 14% of individuals afflicted with this chronic potentially life threatening disorder.[34] Thickening and calcifications of the airway walls can be seen on chest CT while bronchoscopy reveals inflammation, malacia and varying degrees of circumferential airway narrowing.

Malignancy can destroy portions of the tracheobronchial wall, including the cartilage, causing focal malacia such as that seen in tracheal or bronchial

cancers or extralumenal tumours extending into and destroying the airway walls. These include mainly lung[54] and thyroid[55] cancers. These neoplasms may invade and destroy the airway walls causing malacia usually in association with airway stenosis.

Mechanical anatomic factors, as seen after pulmonary resections, produce stenosing tracheobronchial deformities, namely the postpneumonectomy syndrome. Malacia is also noted after treatment of postpneumonectomy syndrome by mediastinal repositioning.[17] In this setting, the affected airway that was previously stretched over the spine or aorta becomes soft.[17] Tracheal and bronchomalacia, usually at or below the site of airway anastomoses has been described after lung and heart–lung transplantation. Its occurrence seems to be more common in patients with obliterative bronchiolitis, chronic rejection, or repeated lower respiratory tract infections, although it may also be related to suturing technique and methods of lung preservation.[56]

Chronic infections can cause progressive weakening of the airway walls because of a persistent inflammatory process which may result in progressive destruction or atrophy of cartilaginous rings. Iwamoto *et al*. have recently reported the use of endobronchial ultrasound (EBUS) to identify destruction of cartilage layers in the tracheobronchial wall in a patient with tuberculosis-related TBM.[57]

Chronic compression of the tracheobronchial tree is seen in substernal goitres, mediastinal tumours or vascular anomalies. Vascular rings have been reported in adults, including double aortic arch and right aortic arch with an aberrant left subclavian artery and ligamentum arteriosum.[58] The likely mechanisms responsible for malacia in such circumstances include thinning of the tracheobronchial wall due to long-term compression or impairment in vascular supply. Malacia of the trachea or main bronchi can also occur because of direct compression or after a late division of a vascular ring.[17] When goitres are removed, occasionally the tracheal walls collapse and extubation is unsuccessful. Dependent on the patient's comorbidities, malacia in these settings may cause substantial airway compromise and respiratory failure prompting intubation, airway stenting, or tracheotomy.[59–62]

Congenital Tracheobronchomegaly also known as Mounier–Kuhn syndrome (MKS) is characterized by atrophy or absence of longitudinal elastic fibres and thinning of the muscularis mucosa.[63] The majority of patients, however, are diagnosed in adulthood.[63]

The Ehlers–Danlos syndrome (EDS) describes a heterogeneous group of inherited connective tissue disorders characterized by skin hyperextensibility, joint hypermobility and tissue fragility. In a series of 32 patients with EDS, only two patients (6.25%) had laryngo-tracheomalacia presumably related to compression by dilated aortic and pulmonary arteries.[64]

Thyroid disease and its association with TBM are well documented.[59–61,65–68] Malacia can be caused by prolonged compression of the trachea by a mass, especially within the confines of the thoracic inlet, tracheal cartilaginous ring involvement by tumour, or most commonly after thyroidectomy, especially in patients with cancer.[62]

Endobronchial electrosurgery has been reported as a cause of cartilage damage and bronchomalacia in animal models[69] and humans.[70] van Boxem *et al*. applied electrocautery with a blunt tip probe for 1–5 s at 30 W to bronchi in to-be resected specimens immediately before patients underwent open lung resection for lung cancer.[70] Necrosis, ulceration and cartilage injury were noted when application time was greater than 3 s.

COPD and asthma are often accompanied by EDAC. Since Herzog's report from 1954, there have been numerous reports of EDAC associated with COPD and asthma, even though it was frequently referred to as TBM or tracheobronchial collapse.[2,4,11–13,71] Presumably, chronic inflammation contributes to the atrophy of the elastic fibres of the membranous portion of the tracheobronchial wall.[13]

DIAGNOSIS

Signs and symptoms

The signs and symptoms of TBM and EDAC are nonspecific and are often similar to those of patients with chronic lung disease such as emphysema or asthma. Dyspnoea, difficulty clearing secretions, recurrent bronchitis or pneumonia, cough and syncope during episodes of coughing might prompt a physician visit.[2,11,13,16,17,50,72] EDAC is also an occasional cause of pulmonary oedema[73] Physical examination may reveal wheezing, rhonchi, decreased breath sounds or poor air movement.[2]

Dyspnoea, expiratory dyspnoea worsening with exertion and cough were the main presenting complaints in at least three published studies of TBM.[2,11,13] Cough, described as a characteristic, seal-like barking presumably occurs because of expiratory collapse and vibration of the floppy membranous wall against the anterior airway wall.[17] Although wheezing was present in 51% of patients, asthma-like exacerbations characterized by wheezing and dyspnoea were less common (17%), but when present were usually refractory to corticosteroids and bronchodilators.[12,13] Haemoptysis may occur from coughing or with associated bronchitis,[2] but was the only finding in 3.5% of patients in a study by Jokinen.[74] TBM and EDAC may actually be among the most common causes of chronic cough in non-smokers.[23] In a series of 78 nonsmoking patients, airway narrowing or collapse was identified in 14.1% of patients with cough lasting more than 3 weeks and normal findings on plain CXR.[23]

Progressive hypercapnic respiratory failure requiring mechanical ventilation has been reported in patients with TBM.[75,76] In intubated patients, however, malacia and EDAC may not be appreciated easily. First, the ETT partially stents the trachea preventing the expiratory airway collapse. Second, positive-pressure ventilatory support keeps the airway lumen open acting as a pneumatic stent. Once the positive pressure or the ETT is removed, the patient may experi-

ence respiratory distress, wheezing and stridor. Because patients may require reintubation as a result of these symptoms, an unexplained extubation failure should prompt evaluation for TBM and EDAC.[40]

Pulmonary function tests (PFTs)

Pulmonary function tests in TBM or EDAC might show diminished expiratory flow, typical notching on the flow-volume (FV) loop, dynamic airway compression (calculated as slow vital capacity minus FVC), a biphasic FV loop or flow oscillations. These findings are neither sensitive nor specific. Overall, few studies rigorously report results of PFTs in patients with TBM or EDAC.[2–4,77–79] In addition, differences in methodology and disease definition are responsible for considerable variability among those studies that do describe findings.[2,79]

Spirometry may reveal obstruction proportionate to the severity of the disease in certain instances.[2] Campbell evaluated the expiratory airflow pattern in 11 patients with bronchoscopically confirmed tracheobronchial collapse and in seven controls.[4] Tracheobronchial collapse was described as expiratory invagination of the posterior wall of the trachea and main-stem bronchi during forced expiration. Severe obstructive ventilatory impairment was noted in most patients with this finding. Ferguson and Benoist[49] evaluated the effect of CPAP on the physiological measures of airflow and expiratory collapse as assessed by bronchoscopy. Dynamic airway compression associated with forced expiration was estimated as the difference between slow and forced vital capacities.[49] In a case series involving three patients with TBM, these authors found that the mean value of dynamic airway compression decreased when patients were treated with increasing levels of CPAP > 6 cm H_2O.

The expiratory spirogram is helpful for diagnosis of any form of dynamic airway obstruction when a typical notch is noted on the volume time curve.[79] The notch is considered to reflect a sudden diminution of flow at the beginning of expiration when the airway collapses. It is characterized by an initial phase in which a small volume is rapidly exhaled, followed by an upward deflection in the spirogram and then the continuation of exhalation.[2,4,49] Some authors believe, however, that the 'typical notches' seen on expiratory spirograms simply represent mechanical artefacts in the counterbalanced water-filled spirometer and may not be present when different spirometer models are used[4] Overall, spirometry, which measures functional rather than anatomic impairment, is an insensitive test for diagnosing TBM, EDAC or central airway obstruction.

Low maximal flow on flow-volume loops has also been noted. Maximal flow is reached quickly after expiration of a small volume of air. Following the maximal flow, there is a large fall in flow although only a small volume is exhaled. There is subsequently a phase in which flow rate falls very little during the remainder of expiration. This phase is responsible for the long plateau seen on the FV loop such that FV loops from patients with TBM or EDAC may be biphasic, with a linear phase of sharply falling velocity followed by an almost linear phase of slow velocity.[4] Garcia–Pachon reports the presence of flow oscillations on the FV loop in a patient with TBM.[77] Such flow oscillations or saw–tooth appearance, defined as a reproducible sequence of alternating decelerations and accelerations of flow, can also be seen in patients with obstructive sleep apnoea, structural or functional disorders of the larynx, neuromuscular diseases,[78] Parkinson disease, pedunculated tumours of the upper airway and upper airway burns.[80] The overall incidence of flow oscillations is rare (1.4% in a retrospective survey including 2800 FV loops), but can be considered a non-specific indicator of upper airway dysfunction.[78,81] The shape of the expiratory flow-volume tracing is, however, neither sensitive nor specific for either TBM or EDAC.[3]

Radiologic imaging studies (Table 1)

Traditional imaging studies such as CXRs or single slice CT scanning are performed at end-inspiration and do not permit precise assessment of airway collapse necessary to diagnose TBM or EDAC. Cine fluoroscopy, and more recently multi-slice CT and magnetic resonance imaging have greatly enhanced non-invasive visual and quantitative analysis of the central airways.[7–9,82–84]

Cine fluoroscopy was used in the past in patients with suspected malacia (Fig. 2).[11] New CT techniques such as Rapid Electron Beam CT[9] and multislice helical CT,[7] however, allow volumetric acquisition of data at both end-inspiration and during dynamic expiration[82] (Fig. 2). Many investigators use 50% or more reduction in airway calibre between inspiration and expiration to identify TBM.[6–9] Precisions regarding EDAC vs. TBM, however, have not been provided and disagreement also exists regarding how much of a decrease in CSA actually signals clinically significant airway narrowing.[85]

Aquino *et al*. evaluated the accuracy of CT scanning in patients with tracheomalacia diagnosed bronchoscopically.[86] Investigators demonstrated that if a patient had greater than 18% change in CSA in the upper trachea and 28% change in the middle trachea between inspiration and end-expiration, the probability of tracheomalacia was 89–100%. If the change in CSA was less, the probability that a patient did not have tracheomalacia was 95–100%. Boiselle *et al*. advocate the use of new CT imaging to identify airway collapse because it provides several advantages over traditional studies (Table 1).[8] In addition, results from CT imaging correlate well with bronchoscopy findings.[7,86] Because paired inspiratory-dynamic expiratory multislice helical CT potentially doubles radiation dose compared with single-phase acquisition, a low dose (40 mAs) technique for the dynamic portion of the study has been advocated.[82] Zhang *et al*.[6] compared standard-dose and low-dose inspiratory/expiratory CT in regard to accuracy for measuring tracheal lumen in patients with and without airway narrowing confirmed by bronchoscopy and found no significant difference between the two

Table 1 Radiological studies used to diagnose tracheobronchomalacia and excessive dynamic airway collapse

Technique	Advantages	Disadvantages
Cine fluoroscopy	1. Traditional technique 2. Inexpensive	1. Poor display of anatomic detail of the tracheal and paratracheal structures 2. Unable to display simultaneously the anteroposterior and lateral walls of the airway 3. Operator dependent
New CT techniques 1. Multislice helical CT a. Standard dose b. Low dose	1. Allow volumetric acquisition of data at both end-inspiration and during dynamic expiration 2. Reveal air trapping 3. Excellent display of anatomic detail of the airway and adjacent structures 4. Allow objective interpretation and quantitative measurement of the degree of collapse 5. Simultaneous display of the anteroposterior and the lateral walls of the trachea and allows reconstruction of three-dimensional images 6. Correlate well with bronchoscopy findings	1. Paired standard dose inspiratory-dynamic expiratory multislice helical CT potentially doubles radiation dose compared with single-phase acquisition
2. Electron beam tomography	1. Short scanning time of only 50–100 ms allows for continuous acquisition of images of a moving object 2. Correlates well with symptoms and bronchoscopic findings	1. Might miss very short, focal abnormalities 2. High radiation exposure 3. Clinical applicability is limited (labour intensive, requiring 160 images/patient)
Cine magnetic resonance imaging	1. Non-invasive high-resolution imaging with excellent soft tissue contrast 2. Absence of ionizing radiation 3. Identification of vascular structures without iodinated contrast media 4. Allows repeated assessments of the airway lumen during multiple respiratory maneuvers	1. Very limited clinical experience

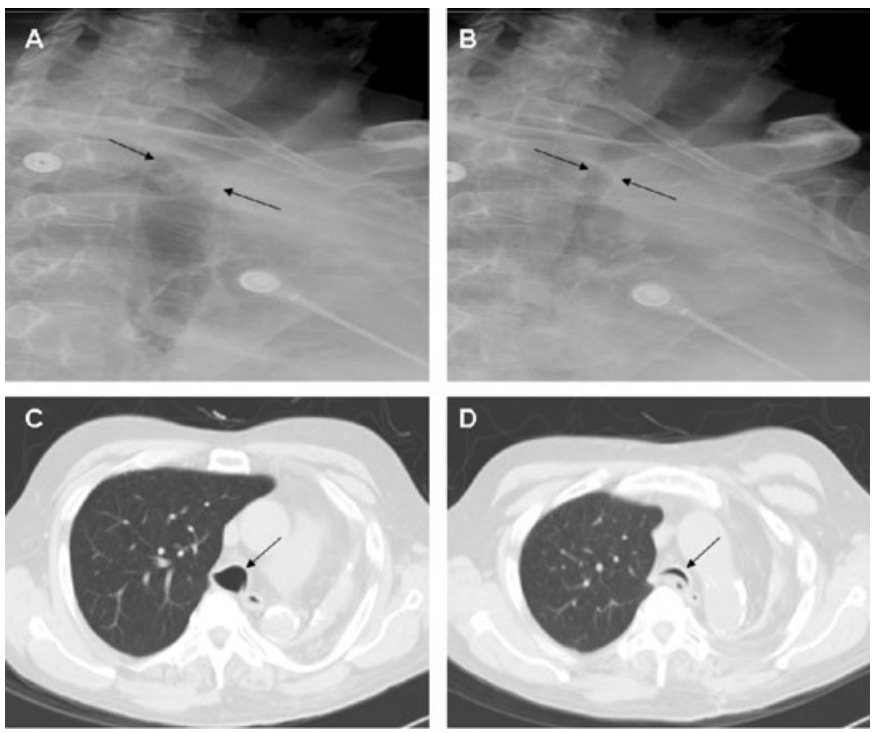

Figure 2 Right antero-oblique view fluoroscopic image during inspiration (A) and expiration (B) shows expiratory collapse of the trachea (arrows) in a patient with severe tracheobronchomalacia (TBM) due to post-pneumonectomy syndrome. Dynamic CT reveals normal tracheal calibre during inspiration (C) and collapse of the anterior tracheal wall resulting in severe crescent type TBM during expiration (D) from the same patient.

methods Electron beam tomography (EBT) was evaluated in a small study involving eight patients with suspected tracheomalacia[9] Good correlation was found between EBT results and clinical symptoms in all patients and limited to good correlation with bronchoscopic findings in six patients.

Cine magnetic resonance imaging appears particularly sensitive for the diagnosis of TBM and EDAC.[83,84] In a small controlled study, Suto[83] showed that a collapsibility index calculated as ((maximum CSA – minimum CSA)/maximum CSA) × 100%) was significantly higher in patients with tracheomalacia than in healthy volunteers during forced inspiration and expiration and during coughing.

Bronchoscopy

Bronchoscopy has been traditionally used to diagnose TBM and EDAC although these entities are rarely described in terms of extent, severity, location and associated anomalies. Although both rigid and flexible bronchoscopy can be performed, flexible bronchoscopy is preferable for diagnosis because the patient is able to breathe spontaneously and follow commands to perform deep breathing, forced exhalation and cough maneuvers to elicit the collapsibility of the airways. There is no universally accepted nomenclature among bronchoscopists, who may not evaluate findings similarly. For example, most investigators have not described whether procedures were performed in the supine or sitting positions, or whether dynamic bronchoscopy was performed. During dynamic bronchoscopy airway dynamics are visualized while moving patients into the supine, upright and lateral decubitus positions and during spontaneous breathing as well as during various maneuvers such as cough, forced expiration, deep inspiration. During these examinations changes in bronchial and tracheal calibre can be measured, extent of collapse is noted, narrowing can be classified as being of the crescent, saber-sheath type or circumferential type, cartilaginous weakening (TBM) can be differentiated from EDAC, and other abnormalities may be discovered (Fig. 3).

The lack of a standard method to quantify the severity of the airway collapse has made serial studies, evaluation of therapies and comparisons between patients difficult. In an effort to eliminate operator-biased descriptions and to improve the accuracy of

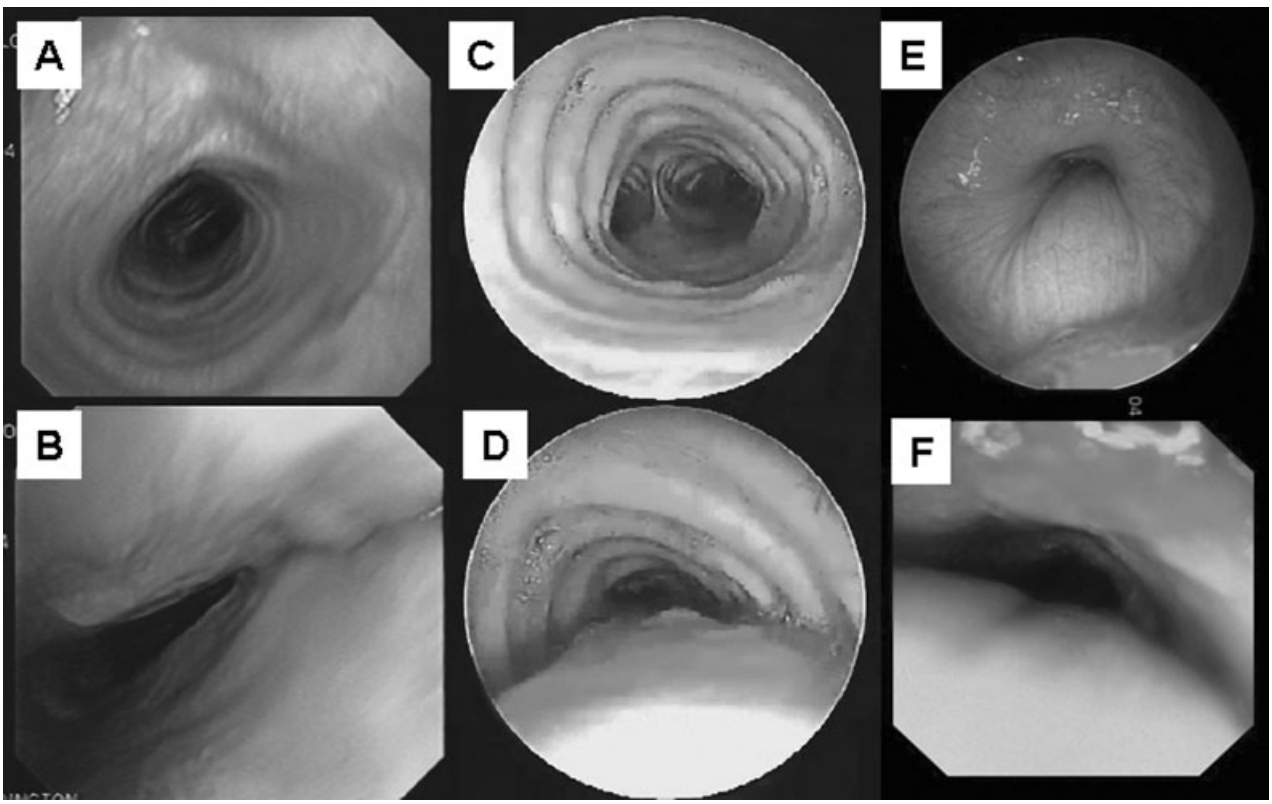

Figure 3 Morphological types of tracheobronchomalacia (TBM) and excessive dynamic airway collapse (EDAC). Trachea during inspiration (A) and expiration (B) in a patient with saber-sheath type TBM. Note the lateral tracheal walls collapse during expiration. In EDAC there is >50% decrease in the airway cross sectional area (CSA) between inspiration (C) and expiration (D) due to excessive bulging of the posterior membrane. Circumferential type TBM occurs when both anterior and lateral airway walls collapse (E). In crescent type TBM there is collapse of the anterior cartilaginous airway wall during expiration (F). While both crescent type TBM and EDAC are characterized by reduction in the anteroposterior diameter during expiration, in EDAC the cartilaginous rings are intact (D) while in crescent type TBM they are collapsed (F).

bronchoscopy, quantitative or morphometric bronchoscopy has been proposed to directly quantify the degree of airway collapse.[49] Baseline recordings of the collapsing airway during inspiration, passive expiration and active expiration are obtained using a video camera attached to the bronchoscope. Selected images can be scanned if necessary, and morphometrically analysed for maximal CSA during inspiration and minimal CSA during passive and active expiration. Expiratory airway collapse is defined as a change in CSA from inspiration to expiration, and can be expressed as a percentage of the maximal inspiratory CSA (i.e. (inspiratory CSA – expiratory CSA)/inspiratory CSA × 100). Rozycki described another bronchoscopic method of quantifying airway collapse by measuring the ratio of the smallest to the largest airway area during a respiratory cycle.[87] The mean smallest/largest airway ratio was significantly lower in patients with TBM, compared with the ratio noted in patients with normal airways.[87] To our knowledge, morphometric bronchoscopy, like complete dynamic bronchoscopy, is seldom, if ever used by most bronchoscopists. Whether this reflects lack of resources, time, or lack of information about the procedures is still unclear. Furthermore, there are technical limitations related to image distortions[88,89] and to date, there are no studies proving the value of these techniques to the decision making process.

Very few studies have compared the accuracy of bronchoscopy with radiological imaging techniques used in the evaluation of TBM or EDAC. In a small study, Hein evaluated the performance of EBT in comparison with conventional bronchoscopy and found limited to good correlations in most patients with TBM.[9] Gilkeson[7] noted good correlation between the degree of dynamic collapse seen on multidetector CT and bronchoscopy in a small number of patients. Larger studies are obviously needed to draw appropriate conclusions.

EBUS permits studies of tracheobronchial wall structure in real time, potentially assisting management.[54,90,91] Using EBUS the tracheobronchial wall appears as a layered structure with distinct hypoechoic and hyperechoic layers corresponding to the laminar structures of the bronchial walls. EBUS has also been reported to demonstrate cartilaginous abnormalities in patients with RP[91] and lung cancer.[54] Inference from these and at least two other reports[57,90] suggests that EBUS might be useful for studying malacia because it can accurately identify the depth of tracheobronchial wall abnormalities[90] and reveal disappearance of cartilage layers in the tracheobronchial wall.[57]

CLASSIFICATION

As of this writing there is no universally accepted classification system for TBM and EDAC. Previously proposed classifications are hampered by unclear definition, measurement criteria, terminology, inaccurate measurement techniques and subjective biases which may explain why none of them has been universally applied by researchers and clinicians alike (Table 2).[11,13,21,39,43,92] None of them reports the morphological types of airway narrowing, nor is functional class emphasized even though patients with different degrees and types of airway collapse may behave differently from a clinical standpoint.

A multidimensional classification system that incorporates results obtained from newer imaging and bronchoscopic modalities, on the other-hand, would allow health care providers to clarify existing questions concerning definitions, diagnosis and management of patients with both TBM and EDAC. A classification system in which degrees of TBM and EDAC are identified according to symptoms, physiological impairment, radiographical appearance, morphological type, degree of airway narrowing, origin and associated abnormalities or comorbidities would facilitate a comprehensive approach to patient care and assist health care providers in evaluating the effects of therapeutic interventions.

TREATMENT

Therapy for patients with TBM and EDAC depends on the severity of symptoms, degree and extent of airway collapse as well as aetiology. In many patients TBM or EDAC are incidental findings and patients are asymptomatic, therefore not requiring therapy. For symptomatic patients, however, medical management should be employed before additional therapeutic modalities such as minimally invasive or open surgical procedures are performed (Table 3).

Medical management

Smoking cessation and therapy similar to patients with COPD, and surgical support of the trachea and the main bronchi in recalcitrant cases has been recommended since 1970s[12,13] Treatment of the underlying condition, when present, must be optimized before initiating or considering other therapies. For instance, if patients have underlying asthma or COPD, treatment should be performed in accordance to previously published guidelines.[93,94] It is noteworthy, however, that in these patients, a dramatic fall in peak flow can occur on PFTs in response to bronchodilators. Although it has not been reported in adults, this phenomenon has been described in paediatric TBM.[35] Because the effect of bronchodilators on central airways is smooth muscle relaxation, the tracheobronchial wall stiffness may further decrease after the administration of bronchodilators and worsen the obstruction caused by malacia or EDAC alone. Therefore, a comprehensive pretreatment evaluation should be performed to distinguish symptoms attributable to TBM or EDAC from those related to underlying diffuse airflow obstruction or parenchymal lung disease. NIPPV can be used to maintain airway patency, facilitate secretion drainage and improve expiratory flow. CPAP acts as a pneumatic stent, decreases pulmonary resistance and improves expiratory airflow obstruction.[95] It also reduces the elevated inspiratory transpulmonary pressures required to

Table 2 Classification systems for tracheobronchomalacia

Author (year) (reference)	Classification characteristics	Comments
Rayl (1965) (92)	**Type I**—proximal and 'subpleural' bronchi **Type II**—mediastinal airways **Type III**—intrapulmonary segmental and distal airways	Classifies tracheo-bronchial collapse during cough Based on cine-bronchographic studies Detailed extent description Severity and aetiology not included
Johnson (1973) (11)	**First degree**—collapse of one half to three fourths of the tracheal lumen with coughing; **Second degree**—three fourths to complete collapse of the tracheal lumen with coughing; **Third degree**—complete collapse of the tracheal lumen; with coughing **Fourth degree**—complete collapse of the tracheal lumen with coughing and ectasia at rest **Focal**—definite localized change in tracheal calibre	Tracheomalacia—diagnosed as more than 50% calibre collapse of the trachea during coughing Based on fluoroscopic studies Provides a severity grading system Extent and aetiology not included
Feist (1975) (43)	**Congenital** **Acquired** tracheostomy Chest trauma chronic irritation inflammation mechanical anatomic factors malignancy	Tracheomalacia—diagnosed as more than 50% calibre collapse of the trachea during coughing Based on fluoroscopic studies Provides incomplete aetiology and morphology criteria Severity criteria not included
Jokinen (1977) (13)	**Severity** *Mild*: obstruction during expiration amounted to one half of the lumen *Moderate*: if it reached three quarters of the lumen *Severe*: if the posterior wall made contact with the anterior wall on slight coughing **Extent** Tracheomalacia Tracheobronchomalacia Bronchomalacia	TBM defined as an expiratory reduction of 50% or more in the anteroposterior calibre of the airways First bronchoscopic classification Defines mild malacia as obstruction of up to one half of the lumen; likely responsible for false positive cases Aetiology not included
Mair (1992) (39)	**Aetiology** **Type 1** is congenital, does not involve external airway compression **Type 2** is due to extrinsic tracheal or bronchial compression **Type 3** is acquired malacia from prolonged increased ventilatory airway pressures, tracheostomy or inflammatory processes causing severe tracheobronchitis. **Severity** *Mild*: less than 70% obstruction *Moderate*: the obstruction was greater than 70% but less than 90% *Severe*: greater than 90% obstruction	Described initially for paediatric tracheobronchomalacia The subtypes may be found in combination with each other Uses an empirical severity score
Masaoka (1996) (21)	**Paediatric type (congenital)** *Localized* *Generalized* **Adult type** *Idiopathic* (trachea and bronchi) *Polychondritic* type (diffuse) *localized* type (idiopathic) **Secondary type** (vascular, traumatic, neoplastic)	TBM described as at least 80% narrowing of a major airway during expiration Classifies paediatric and adult TBM Defines the extent of TBM Coexistence of several subtypes Likely high false (–) rate because of the definition used Aetiology and extent criteria combined

Table 3 Proposed treatment modalities for tracheobronchomalacia and excessive dynamic airway collapse

Treatment	Advantages	Disadvantages
Medical management		
1. Bronchodilators	• Useful in mild cases of EDAC due to asthma and COPD	• May worsen airflow obstruction caused by TBM or EDAC alone
2. CPAP	• Decreases pulmonary resistance • Improves airflow obstruction • Decreases inspiratory work of breathing	• Intermittent treatment • Limited experience • May not suffice as a stand alone therapy for severe cases
3. Disease specific drug therapy	• May suffice in less severe cases due to asthma, COPD or RP	• Concomitant CPAP and/or stent placement often necessary
Minimally invasive surgery		
1. Endolumenal airway stents	• Improve symptoms and PFT • Maintain airway patency • Therapeutic trial before surgery	• Limited data for isolated TBM or EDAC • Stent related complications • Often, multiple stents are required
2. Experimental approaches	• Improvement in symptoms, PFT and bronchoscopic aspects	• Preliminary results in a few patients laser therapy
Open surgery		
1. Tracheostomy	• Stents the airways • If necessary, provides invasive ventilatory support	• Tracheomalacia and stenosis at the stoma site • May exacerbate TBM/EDAC
2. Airway splinting	• Consolidates and reshapes the airway wall • Offers long-term airway support	• Invasive, requires thoracotomy • Complications common with Marlex mesh
3. Tracheal resection	• May be curative for focal malacia	• Experience limited to specialized centres application and efficacy in humans
4. Experimental approaches	• Less complications than other techniques in animal models	• Remains unknown

EDAC, excessive dynamic airway collapse; PFT, pulmonary function tests; RP, relapsing polychondritis; TBM, tracheobronchomalacia.

initiate airflow, therefore decreasing the work of breathing.[96] Small studies showed that spirometry values improved during the acute administration of nasal CPAP.[49] These patients had improved sputum production and atelectasis, improved exercise tolerance and reduced need for medical care long-term even while not using nasal CPAP.[49] Although large controlled studies are needed to confirm these findings, it seems that nocturnal and intermittent daytime nasal CPAP benefits patients with TBM or EDAC especially in less severe cases or can be used as adjunctive therapy to keep the airway opened and facilitate secretion drainage.[31] For patients with systemic conditions responsible for TBM or EDAC, the underlying disease should be controlled first by using disease specific drug therapy. For instance, patients with RP often respond to steroids or other immunosuppressive agents and might not require additional therapy.[34] In cases of airway emergencies or in the presence of symptoms refractory to conservative therapy, however, more aggressive interventions should be considered.

Minimally invasive surgery

Airway stents are often able to restore and maintain airway patency in patients with any form of central airway obstruction (Fig. 4). PFTs improve significantly after stenting of various causes of central airway obstruction, including malacia.[52,54,97–101] More than one stent may be required if the symptoms persist after stenting presumably because of distally migrated choke points.[54] It is difficult, however, to draw conclusions about the efficacy of endolumenal stents pertaining only to TBM and EDAC based on available data.

A dynamic process, such as that seen in TBM and EDAC, continuously changes the shape of the airway during inspiration and expiration, altering the contact between the stent and the airway walls and possibly predisposing a stent to migration or fracture. This is especially true for the studded Dumon-type silicone stent which is probably the most commonly used stent today but is also the most easily collapsible from extrinsic compression.[102] Appropriate selection of the type and size of an airway stent is difficult, especially in patients with large, dynamic airway lumens such as patients with tracheobronchomegaly. Metal stents have also been used over the years with varying results. They are less likely to migrate or to cause obstruction by mucus plugging. These stents preserve mucociliary clearance if uncovered and are capable of a certain degree of dynamic compression during coughing to facilitate mucus clearance. These advantages must be carefully weighed against the substantial disadvantages of metal stents, which are the difficulty with which they can be removed; their tendency to become epithelialized in the airway,

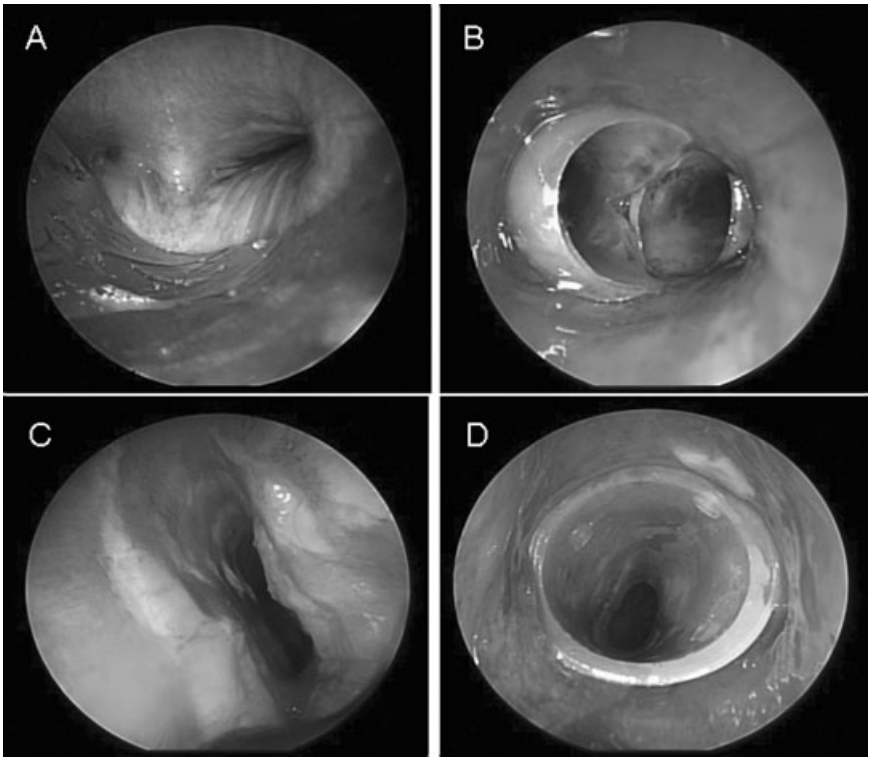

Figure 4 Airway stenting for tracheobronchomalacia (TBM). Severe TBM is visualized in the lower third of the trachea and the main bronchi in a patient with relapsing polychondritis. (A) During rigid bronchoscopy before stenting; (B) After stenting, airway patency is completely restored. TBM (saber-sheath type) localized to the mid portion of the trachea before (C) and after (D) stenting in a patient post surgery for a large thyroid mass.

potentially leading to recurrent stenosis; and their propensity to fracture and collapse. In fact, the Food and Drug Administration has recently issued a warning regarding the use of metal stents in patients with benign airway disorders. Another dilemma of stent insertion is related to the location of expiratory flow limitation. Lehman *et al*. state that placing a stent at the site of maximal collapse during exhalation might result in migration of the choke point upstream, towards the periphery of the lung.[103] This issue has been addressed in patients with central airway obstruction due to lung cancer. The authors positioned the stents at the precise location of expiratory flow limitation, identified by combining EBUS, ultrathin bronchoscopy, flow-volume analysis and three-dimensional CT scanning. Subsequent improvements in dyspnoea and spirometry were noted after secondary stent insertion.[54] If stent insertion does not improve patient symptoms, stent removal is warranted to avoid complications. Migration, obstruction by mucus or granulation tissue, infection, fracture and airway perforation are well described in the literature.[102–105] The distinction between stent-related adverse events and symptoms related to TBM or EDAC, however, may be difficult to assess based on clinical grounds. Therefore, new onset of symptoms should prompt immediate inspection bronchoscopy.[106,107]

Open surgery

In selected cases, in specialized centres, surgery should be employed for functionally disabling TBM or EDAC that failed other therapies. Most surgical studies are hampered with the same problems noted in medical studies; namely lack of standardized definitions, classification and incomplete pre- and post-intervention assessment. The most experience is in disease secondary to emphysema and chronic bronchitis. Prior to proposing an open surgical intervention, an easily removable stent should be considered as a trial to identify those patients who are likely to benefit from surgery in the long term.[40] Several surgical procedures have been performed over the years but most are presented as small case series or case reports with unclear outcome variables.

Tracheostomy may stent the malacic airway, provides invasive ventilatory support when necessary[62,66,67,108] and offers a secured airway in cases of acute airway obstruction. The tracheostomy tube alone may be effective if it bypasses the affected malacic segment, especially in cases of focal, cervical TBM. Tracheostomy, however, can be complicated by secondary tracheomalacia and stenosis at the stoma site.[109] In addition, from a physiological standpoint, tracheostomy may be inadequate and may exacerbate diffuse malacia or EDAC because it bypasses the physiological function of the glottis to maintain positive transmural pressure that keeps the airway lumen patent.[62] It should not be considered a first line treatment in elective cases. Tracheal resection has been proposed by Grillo for post-intubation, focal tracheomalacia.[110] In this report, outcome was good to satisfactory in 93% of patients and mortality was 2%.

Airway splinting refers to various surgical techniques used to consolidate and reshape the airway wall, as well as to reinforce the posterior membrane in

cases of TBM and EDAC. Several surgical methods have been described. Spanplasty has been used to reinforce the membranous portion of the trachea in crescent–type malacia.[45,50] An alternative approach developed by Hanawa allows fixation of the cartilaginous portion of the trachea by using a Marlex mesh (silastic membrane-reinforced crystalline polypropylene and high-density polyethylene).[50] Other methods of airway splinting include tying the posterior wall of the trachea with bone chips, fascia grafts or plastic prostheses,[50] performing autologous costal cartilage grafts to support the tracheal wall[111] and suturing the trachea to dura mater grafts.[112] Biocompatible ceramic rings have been successfully used to restore the normal airway calibre and improve the lifestyle in 16 patients.[113] Surgical placement of external tracheal stents has been advocated for severe cases of malacia and EDAC.[114–116] Because of the minimal mucosal reaction, these stents allow normal secretion clearance. Stents made by resorbable biopolymers temporarily strengthen the malacic segment and do not need to be removed once tracheal stability is achieved.[115,116] In animal models, resorbable poly-L-lactic acid-polyglycolic acid (PLPG) stent placement was followed by rapid and consistent recovery of respiratory function, as well as preservation of the respiratory epithelium and normal cartilaginous growth.[115] Furthermore, in a controlled animal study, the external resorbable PLPG stents were superior to internal metal Palmaz stents in terms of respiratory distress, tracheal stenosis and inflammation.[114] The applicability of these stents in adults with TBM remains to be established because the PLPG stents are resorbed after 1 year and acquired malacia is unlikely to regress spontaneously unless permanent airway remodelling is initiated by stent placement.

Experimental approaches

Studies showed that injecting sclerosing agents into pericartilaginous tissues resulted in significant peritracheal fibrosis compared with controls.[117] An innovative concept therefore is the use of laser therapy to strengthen the posterior membrane. Fibrosis of the posterior wall presumably tightens the airway walls and prevents EDAC.[72] Attempts to achieve a fibrotic response after laser application are plausible but hazardous. The posterior wall is only 3–5 mm thick and, to our knowledge, no experimental studies have yet been performed examining laser–tissue interactions at the level of the posterior membrane of animal models. Preliminary results in a few patients, however, suggest improvement in symptoms, ventilatory

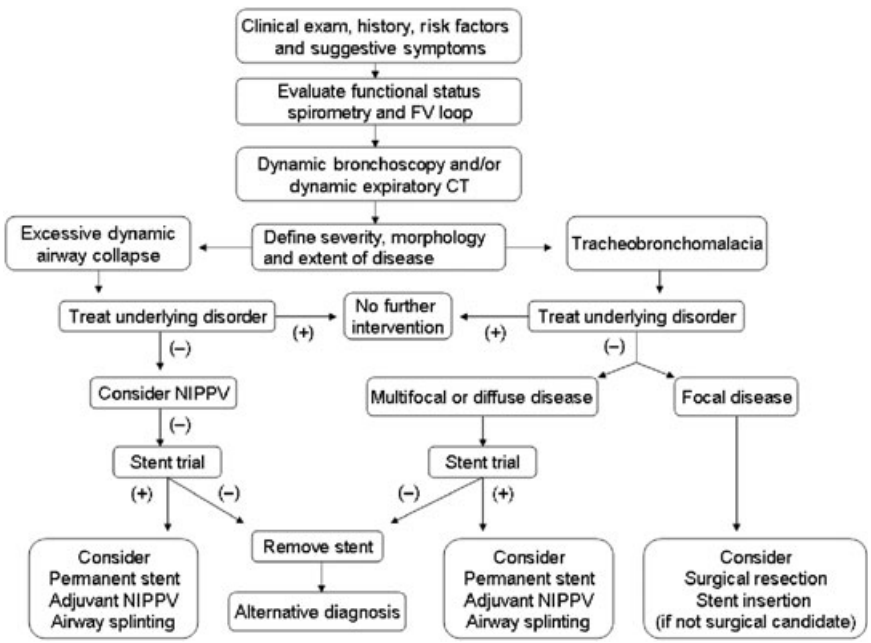

Figure 5 Diagnostic and management algorithm for tracheobronchomalacia (TBM) and excessive dynamic airway collapse (EDAC).[121] After pulmonary function tests and functional status assessment, bronchoscopy and/or dynamic expiratory CT define the severity, extent and morphology of the disease. For EDAC, first treat the underlying asthma or COPD, when present. If no improvement, consider intermittent nasal CPAP. In refractory cases, a stent trial is warranted. Other therapeutic alternatives depend on clinical status, operator experience and availability. For good surgical candidates, airway splinting can be considered. Alternatives include permanent stent insertion with or without adjuvant non-invasive positive pressure ventilation (NIPPV). For TBM, the underlying disease (i.e. relapsing polychondritis) should be treated first. Definitive therapy depends on the extent of the disease. Surgical resection of the affected segment may be the therapy of choice for focal TBM. For multifocal or diffuse disease a stent trial may be warranted. If there is objective improvement, then permanent stent insertion should be considered. NIPPV can also be used. Airway splinting should be reserved for refractory cases and good surgical candidates. +, improvement; –, no improvement; FV, flow volume.

function and bronchoscopic aspects.[72] Long-term outcomes have not been reported. Other experimental approaches include tracheal reconstruction using autologous peri-ostial grafts,[118] polytetrafluoroethylene grafts[119] and cartilage regeneration using slow release of bone morphogenetic protein-2 from gelatine sponge.[120] The results of these experimental techniques to treat TBM are encouraging, but their application and efficacy in humans remain to be determined.

SUMMARY

Adult TBM and EDAC may be idiopathic or acquired, autonomous or associated with other disorders. Both conditions represent dynamic forms of central airway obstruction that are differentiated by bronchoscopic and radiological imaging studies. TBM is characterized by a weakness of the tracheobronchial cartilaginous structures whereas EDAC is marked by excessive bulging of the posterior membrane into the airway lumen during exhalation. TBM and EDAC present with a variety of symptoms ranging from mild shortness of breath and cough to respiratory failure. Diagnosis may be suggested by symptoms and PFT but is confirmed by dynamic imaging studies or bronchoscopy. It is not known whether combining radiological and bronchoscopic techniques improves the diagnostic yield or contributes to changes in the proposed management of these disorders. A multidimensional classification system to objectively compare patients with TBM and EDAC would assist researchers and clinicians in answering questions regarding physiology, histopathology and therapeutic management.

In the critically ill patient, as in other cases of central airway obstruction, it is important to restore oxygenation and ventilation immediately. Further interventions, which include conservative medical management, minimally invasive procedures and open surgical interventions, are based on the nature and severity of the dynamic obstruction, functional status, access to complex diagnostic and therapeutic techniques, and degree of medical and surgical expertise available. Current evidence and a multidisciplinary, patient-centred approach to these two disease processes allow the formulation of algorithms of care similar to the ones included herein (Figs 5,6), as well as to those proposed by others.[40]

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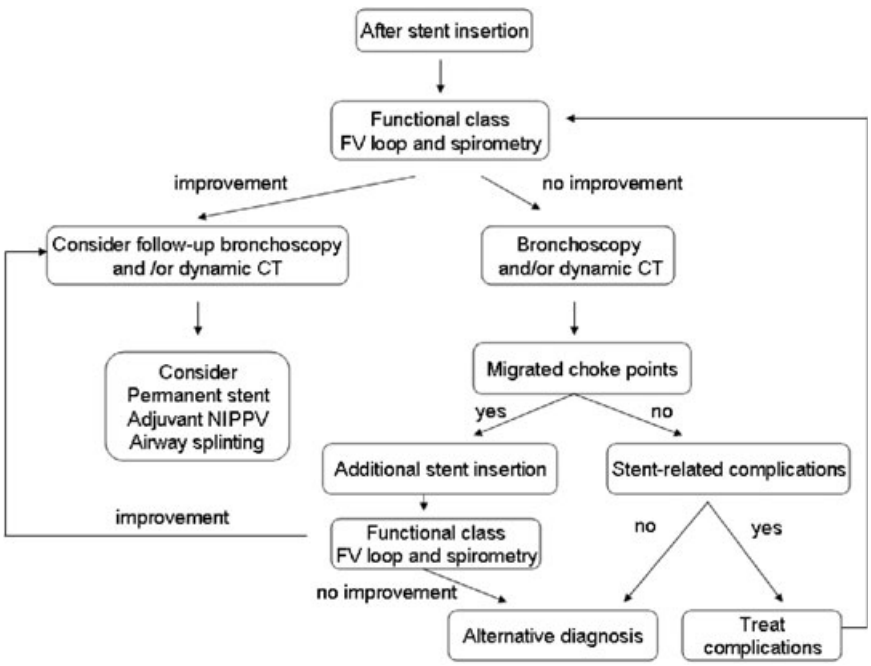

Figure 6 Management algorithm after stent insertion.[122] Functional status and pulmonary function tests objectively document the changes in maximal expiratory flow and symptoms. If the patient improves, decision about surgery or permanent stent insertion should be taken only after documented symptomatic, bronchoscopic or radiological improvement on follow-up studies. If there is no improvement, then bronchoscopy and or/dynamic expiratory CT should be performed to search for migrated choke points. Stenting the new choke points should be considered, if present. In case of improvement, follow up at regular intervals should be performed. If there is no documented improvement after secondary stent insertion, then an alternative diagnosis should be considered. If after the initial stent insertion there is no improvement and there are no migrated choke points, stent related complications should be suspected. FV, flow volume; NIPPV, non-invasive positive pressure ventilation.

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