Multidetector CT Evaluation of Tracheobronchomalacia

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KEYWORDS

- Tracheomalacia
- Tracheobronchomalacia
- Bronchomalacia
- Multidetector computed tomography (MDCT)
- Clinical indications • Diagnostic criterion
- MDCT protocols • Image interpretation

Tracheobronchomalacia (TBM) is a disorder that results from a weakness of the tracheobronchial walls and/or supporting cartilage, resulting in excessive expiratory collapse (**Fig. 1**).[1–5] This condition may arise congenitally from disorders related to underlying impaired cartilage maturation or may be acquired from conditions related to prior intubation, infection, trauma, long-standing extrinsic central airway compression, or chronic inflammation.[1–5]

Although TBM has been increasingly recognized as an important cause of chronic respiratory symptoms, it is still considered a relatively underdiagnosed condition.[3] Because it escapes detection on routine end-inspiratory chest radiographs and CT scans, the diagnosis of TBM usually requires evaluating the airway during an active respiratory maneuver such as dynamic exhalation or coughing.[3,4,6] Recent advances in CT technology now allow the radiologist to accurately diagnose this condition noninvasively with similar accuracy to bronchoscopy, the historical reference standard.[6,7]

This article provides an up-to-date review of imaging for TBM, including clinical indications, physiologic principles, diagnostic criterion, multidetector CT (MDCT) protocols, multiplanar and 3-dimensional images, image interpretation, and pre- and postoperative assessment. An emphasis is placed on providing the reader with practical information that will enhance the ability to optimally perform and interpret CT studies for diagnosing TBM in daily clinical practice.

CLINICAL INDICATIONS

Although clinical indications have yet to be established for screening for TBM, the combination of chronic respiratory symptoms and one or more risk factors should raise the suspicion for this disorder. Risk factors for the acquired form of TBM are reviewed in **Box 1**.

It is important to be aware that extrinsic airway compression caused by paratracheal masses (such as mediastinal vascular anomalies and thyroid goiters) is frequently associated with tracheomalacia (TM) (**Fig. 2**).[3,8,9] For example, in children with paratracheal vascular anomalies such as innominate artery compression or vascular rings, surgical correction of the vascular anomalies alone may not adequately treat the respiratory symptoms if extrinsic compression is accompanied by intrinsic TM.[8,9] Thus, preoperative evaluation of

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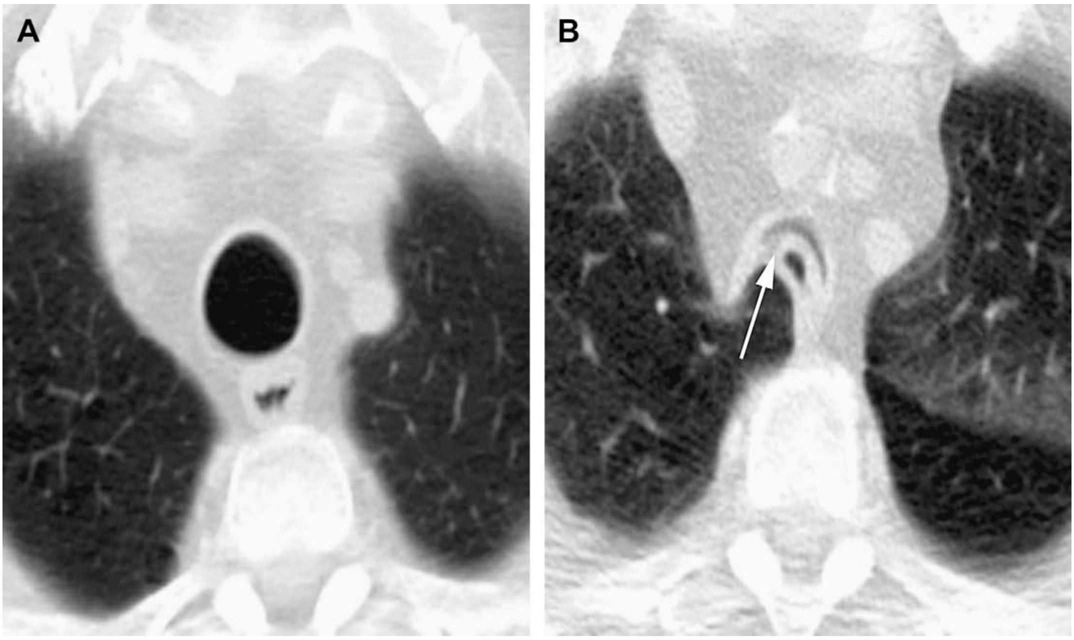

Fig. 1. CT diagnosis of TM in a 72-year-old man with shortness of breath. Paired inspiratory CT image (*A*) demonstrates a normal oval shape of the tracheal lumen. Dynamic expiratory CT image (*B*) shows excessive expiratory collapse of the trachea (*arrow*) consistent with TM.

such patients should routinely include a dedicated expiratory sequence to assess for TM.

Although pulmonary function studies (PFTs) are potentially useful in evaluating a patient with suspected TBM, they are not diagnostic of this entity.[3] On forced expiratory spirograms, patients with TBM frequently show a characteristic "break" or notch in the expiratory phase of the flow-volume loop;[3] however, this pattern may also be seen in patients with emphysema without coexisting TBM. Thus, MDCT is still necessary for confirming and characterizing TBM in such patients.

PHYSIOLOGIC PRINCIPLES

Functional CT imaging for TBM requires acquiring imaging data either during or after a provocative maneuver such as expiration and coughing. In order to understand why certain respiratory maneuvers are more effective than others at eliciting tracheal collapse, it is important to review the relationship of tracheal collapse to intrathoracic pressures. Changes in size of malacic trachea and bronchi depend on the difference between the intraluminal pressure inside the airways and the pleural (intrathoracic) pressure outside.[4,10] Pleural pressure depends mostly on respiratory muscles, and is high during expiratory efforts. In contrast, intraluminal pressures are highly variable, and depend on airflow. When airflow is zero, intraluminal pressure equals alveolar pressure and differs from pleural pressure only by the elastic recoil pressure of the lung, which depends on lung volume. At maximal lung volume with no flow (end-inspiration), the intraluminal pressure is 20 to 30 cm H_2O greater than pleural pressure, and the pressure difference expands the trachea.

Box 1
Risk factors for acquired tracheomalacia

- Chronic obstructive pulmonary disease
- Iatrogenic
  - Prior intubation
  - Prior tracheostomy
  - Radiation therapy
  - Lung transplantation
- Chronic bronchitis
- Relapsing polychondritis
- Chest trauma
- Chronic external compression of the trachea
  - Paratracheal neoplasms (benign and malignant)
  - Paratracheal masses (eg, goiter, congenital cyst)
  - Aortic aneurysms and vascular rings
  - Skeletal abnormalities (eg, pectus, scoliosis)

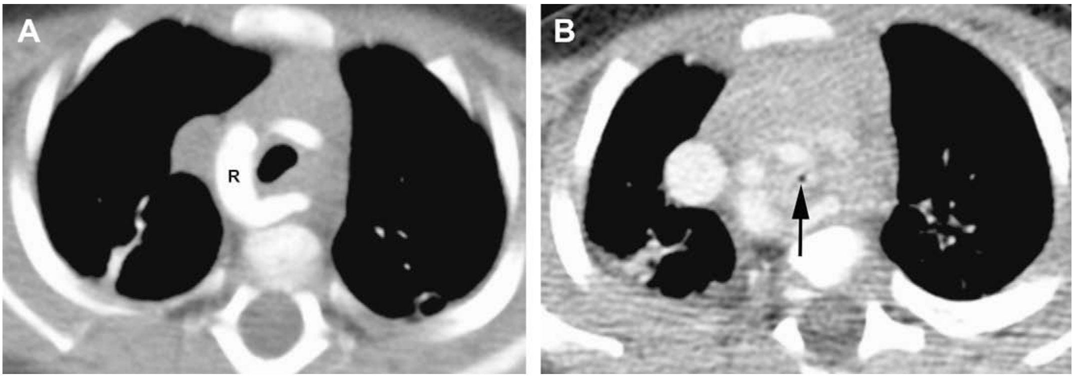

Fig. 2. TM in a young child associated with extrinsic compression from mediastinal vascular anomaly. Inspiratory contrast-enhanced CT image (*A*) demonstrates mild tracheal compression from a right-sided aortic arch (R) with aberrant left subclavian artery. Dynamic expiratory CT image (*B*) at similar level demonstrates near collapse of the trachea (*arrow*), consistent with severe TM. Prominent thymic tissue is noted in the mediastinum, consistent with the patient's young age.

At low lung volumes with no flow (end-expiration), the intraluminal pressure is nearly equal to pleural pressure, and the trachea is unstressed. The trachea is most compressed during cough and dynamic expiration at low lung volume, when pleural pressure is high ($\sim$100 cm H_2O), and expiratory flow limitation in the small airways prevents transmission of the high alveolar pressures to the central airways. Under these conditions, intraluminal pressure is nearly atmospheric, and the large transmural pressure causes tracheal collapse.[4,10]

Thus, based on physiologic principles, imaging during a forced exhalation or coughing maneuver is more sensitive for eliciting TBM than imaging at end-expiration.

DIAGNOSTIC CRITERION

Although greater than 50% expiratory reduction in cross-sectional area of the airway lumen is widely considered diagnostic of TM, it is important to be aware that asymptomatic, healthy individuals may demonstrate levels of expiratory collapse that exceed this diagnostic threshold (**Fig. 3**). For example, Stern and colleagues[11] obtained a degree of tracheal collapse greater than 50% at end-expiration in 4 of 10 healthy young adult male volunteers scanned with an electron-beam CT. Based on their findings, these authors recommended a more conservative threshold of 70% of collapse as indicative of TM. Similarly, Heussel and colleagues[12] reported that healthy volunteers can sometimes exceed the standard diagnostic criterion. Moreover, when using 64-MDCT "cine" imaging to assess the trachea during coughing, it has been suggested that a higher threshold value of 70% should be considered when using this robust provocative maneuver to elicit tracheal collapse.[13]

Based on the results of these studies, there is a need to obtain normative data regarding the range of tracheal collapse using forced exhalation among patients of varying ages, ethnicities, and both genders, both with and without coexistent pulmonary disease. Until such data are published, one should keep in mind that there is substantial overlap with normal physiologic changes at the lower range of positive results. Thus, MDCT results should be carefully correlated with respiratory symptoms and functional impairment.

MULTIDETECTOR CT TECHNIQUES

Three main types of MDCT techniques are currently used for evaluating TBM: (1) paired end-inspiratory and end-expiratory MDCT; (2) paired end-inspiratory and dynamic expiratory MDCT; and (3) cine MDCT combined with a coughing maneuver.

Paired End-Inspiratory/End-Expiratory Multidetector CT

With this method, inspiratory and expiratory phases of volumetric CT data acquisition are obtained at the end of inspiration and expiration, respectively. Because imaging at the end of expiration is the least sensitive method for eliciting expiratory collapse, this technique should be limited to the assessment of infants and children younger than 5 years of age who are unable to cooperate with dynamic expiratory breathing instructions. For such patients, end-inspiratory and end-expiratory phases of the CT scanning are obtained following intubation by alternatively applying and withholding positive pressure

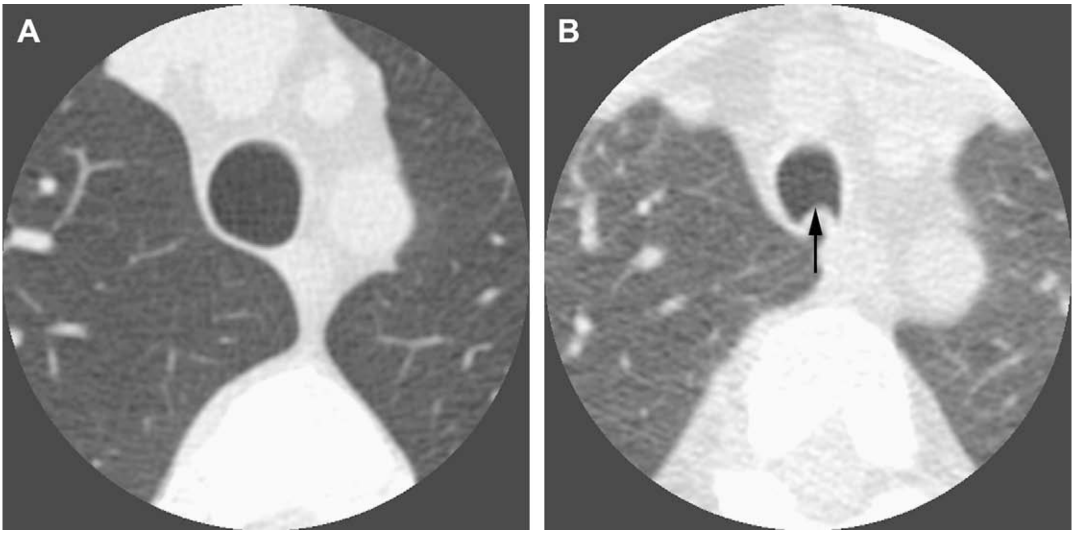

Fig. 3. Dynamic tracheal changes in a 45-year-old asymptomatic male volunteer with normal pulmonary function. Axial end-inspiratory CT image above level of aortic arch (*A*) demonstrates normal oval-shaped tracheal lumen. Axial dynamic-expiratory CT image at same level (*B*) demonstrates moderate anterior bowing of posterior membranous wall of trachea (*arrow*). Cross-sectional area of the tracheal lumen decreased by 51% during expiration, slightly exceeding the diagnostic criterion for TM.

ventilation during inspiration and expiration, respectively.[8,9] For detailed information about this method, the reader is referred to Lee and colleagues.[8,9]

Paired End-Inspiratory/Dynamic Expiratory Multidetector CT

This technique includes imaging during two different phases of respiration: end inspiration (imaging during suspended end inspiration) and continuous dynamic expiration (imaging *during* forceful exhalation). This protocol can be successfully performed with any type of MDCT scanner. However, the best results are produced with scanner configurations of eight or more detector rows.

At the authors' institutions, this technique is the method of choice for imaging adults and children older than 5 years for suspected malacia. In the following paragraphs, scanning parameters for imaging adults are reviewed. For detailed information about imaging children with this protocol, the reader is referred to Lee and colleagues.[8,9]

Before helical scanning, initial scout topographic images are obtained to determine the area of coverage, which extends from the proximal trachea through the main bronchi, corresponding to a length of approximately 10 to 12 cm in adults. If the patient has not had a recent CT scan, the end-inspiratory acquisition can be extended to include the entire lungs to assess for potential complications of malacia such as bronchiectasis. Helical scanning is performed in the craniocaudal direction for both end-inspiratory and dynamic-expiratory scans.

The end-inspiratory scan is performed first (170 mAs, 120 kVp, 2.5 mm collimation, pitch equivalent of 1.5). Following the end-inspiratory scan, patients are subsequently coached with instructions for the dynamic expiratory component of the scan (40 mAs, 120 kVp, 2.5 mm collimation, high-speed mode, with pitch equivalent of 1.5). For this sequence, patients are instructed to take a deep breath in and to blow it out *during* the CT acquisition, which is coordinated to begin with the onset of the patient's forced expiratory effort. Detailed "scripts" of breathing instructions for this protocol can be found in an article by Bankier and colleagues.[14]

Cine CT During Coughing

This technique requires use of a 64-row or greater MDCT scanner. At the authors' institution this protocol is performed with detector collimation 0.5 mm $\times$ 64; mA = 80; kVp = 120; gantry rotation = 0.4 seconds.

An initial scout topographic image is obtained to determine the area of coverage, which extends 3.2 to 4.0 cm in craniocaudad length depending on the scan manufacturer. In order to "sample" the trachea and proximal main bronchi within a single acquisition, the inferior aspect of the acquisition is set at the level of the carina, and the superior aspect of the acquisition is set 3.2 cm above this level, which corresponds to approximately the level of the aortic arch in most adults. A 3- to 5-second acquisition is acquired in cine mode beginning at end-inspiration and followed by repeated coughing maneuvers. Images are reconstructed at 8-mm collimation in a standard algorithm, creating four contiguous cine datasets from a single acquisition.

The recently introduced dynamic-volume 320 MDCT scanner (Aquilion ONE, Toshiba Medical Systems) provides 16 cm of anatomic coverage in a single rotation.[15] This technique holds great promise for evaluating TBM because it provides coverage of the entire intrathoracic trachea in most older children and adults.

Radiation Exposure

Because paired inspiratory-expiratory CT requires imaging during two phases of respiration, it has the potential to result in a "double dose" compared with a traditional single-phase CT scan unless methods for dose reduction are used. Cine imaging also has the potential for high radiation exposure.

Because of the high inherent contrast between the air-filled trachea and soft tissue structures, it is possible to substantially reduce dose without negatively influencing image quality for assessing luminal dimensions of the airway.[4,6] For example, a clinical study by Zhang and colleagues[16] showed no difference between standard (240 to 260 mA) and low-dose (40 to 80 mA) images for assessing the tracheal lumen during dynamic expiration.

Thus, a low-dose (30 to 40 mAs) technique should be used when imaging during coughing or expiration. Although a standard mAs level is typically used for the end-inspiratory scan, dose modulation can be used to modify the mAs level during the acquisition to further reduce radiation exposure.

The estimated radiation dose (expressed as dose-length product) for a dual-phase study (standard-dose end-inspiratory sequence + low-dose dynamic expiratory sequence) for a 70-kg patient is approximately 500 mGy.cm, which is comparable to a routine chest CT (reference value 600 mGy.cm).[17] By comparison, the estimated dose for a low-dose cine CT is approximately 200 to 220 mGy.cm. However, unlike the dual-phase scan, which covers the entirety of the central airways, a single cine acquisition covers only 3.2 to 4.0 cm in the z-axis (depending on the scanner configuration). If repeated at multiple levels to provide similar coverage to the dual phase CT, the total dose for serial cine acquisitions would be greater than the dual-phase technique. Estimated doses for cine imaging of the airways using the new 320 MDCT scanner are not currently available, but careful attention to dose reduction methods will be important with this scanner to avoid excessive radiation exposure.

Image Quality

In order to ensure a high-quality study, technologists should be trained to coach and monitor patients as they perform the respiratory techniques. Technologists should also be trained to recognize the characteristic appearance of inspiratory and expiratory CT scans to ensure that the imaging sequences have been successfully performed during the appropriate respiratory maneuvers (see **Fig. 1**). For sites using these protocols for the first time, the radiologist should observe and monitor cases until the technologists have become comfortable coaching patients with these maneuvers.

ROLE OF MULTIPLANAR AND 3-DIMENSIONAL RECONSTRUCTIONS

Volumetric MDCT imaging allows for the creation of high-quality, three-dimensional (3D) reconstructions and multiplanar reformations (MPR), which have the potential to aid diagnosis and preoperative planning.[4,18–21] Virtual bronchoscopic images, which provide an intraluminal perspective similar to conventional bronchoscopy, are particularly helpful for assessing dynamic changes in the lumen of the main bronchi, which course obliquely to the axial plane and are not optimally evaluated by traditional axial CT images. External 3D reconstructions are valuable for displaying complex 3D relationships in patients with extrinsic paratracheal masses such as aortic vascular anomalies.

Paired end-inspiratory and dynamic-expiratory sagittal reformation images along the axis of the trachea are helpful for displaying the craniocaudad extent of excessive tracheal collapse during expiration (**Fig. 4**).[4]

IMAGE INTERPRETATION

Interpretation of CT images requires careful rev iew and comparison of both end-inspiratory and dynamic-expiratory images.

End-inspiratory images provide important anatomic information about tracheal size, shape, and wall thickness, as well as the presence or absence of extrinsic masses compressing the

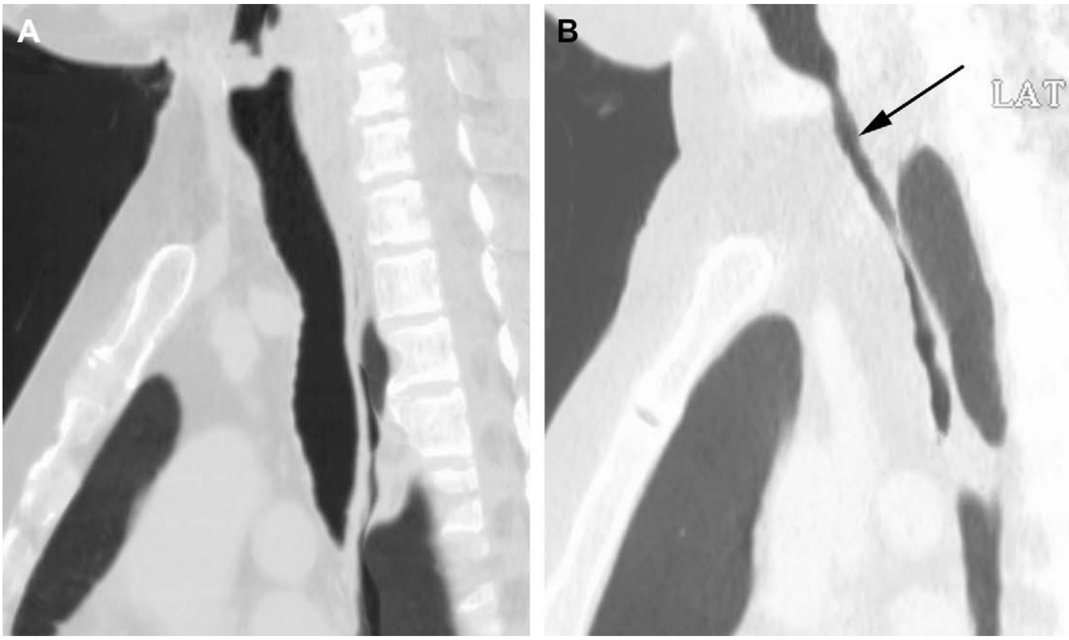

Fig. 4. Assessment of craniocaudad extent of TM in a 50-year-old woman with chronic cough. Paired end-inspiratory (*A*) and dynamic-expiratory (*B*) sagittal reformation images enhance display of craniocaudad length of TM. Note diffuse expiratory narrowing of trachea during expiration (*B*), consistent with diffuse TM.

trachea. In patients with TM, the tracheal lumen is almost always normal in appearance on end-inspiration CT.[2] There are four notable exceptions. First, patients with relapsing polychondritis (**Fig. 5**) frequently demonstrate characteristic wall thickening and calcification that spares the posterior membranous wall of the trachea. Second, patients with lunate (coronal > sagittal dimension) tracheal configurations (**Fig. 6**). Third, patients with tracheomegaly (coronal diameter > 25 mm). Fourth, patients with extrinsic tracheal compression from adjacent vascular anomalies or thyroid masses (see **Fig. 2**).

When there is near or complete collapse of the airway lumen during expiration, the diagnosis of malacia can be confidently made based on visual analysis of the images (see **Fig. 1**). However, the most accurate means for diagnosing malacia on CT in patients with subtotal expiratory collapse is to use an electronic tracing tool to calculate the cross-sectional area of the airway lumen on images at the same anatomic level obtained at inspiration and dynamic expiration (**Fig. 7**).[4] Such tools can be found on commercially available picture archiving and communication systems stations as well as with 3D workstations.

As described in the previous section, greater than 50% expiratory reduction in cross-sectional area is considered diagnostic. Care should be taken to ensure that the same anatomic level is compared between the two sequences by comparing vascular structures and other anatomic landmarks.

Although quantitative methods are preferable to visual assessment, it is important to be aware that about half of patients with acquired TM will demonstrate an expiratory "frown-like" configuration, in which the posterior membranous wall is excessively bowed forward and parallels the convex contour of the anterior wall with less than 6-mm distance between the anterior and posterior walls (**Fig. 8**).[22] This appearance, which has been coined the "frown sign," has the potential to aid the detection of TM when patients inadvertently breathe during routine CT scans.[22]

With regard to interpreting cine coughing CT studies, these exams are ideally viewed in "cine" fashion at either a picture archiving and communication systems workstation or 3D workstation. Quantitative measurements are obtained on individual static images in a similar fashion to the technique described for paired-inspiratory–dynamic-expiratory CT. As described earlier, greater than 70% reduction in cross-sectional area during coughing is considered diagnostic. A commercial software program (Analyze 6.0, AnalyzeDirect, Inc., Lenexa KS) can also be used to provide automated measurement of changes in tracheal lumen cross-sectional area values during the cine sequence.[13]

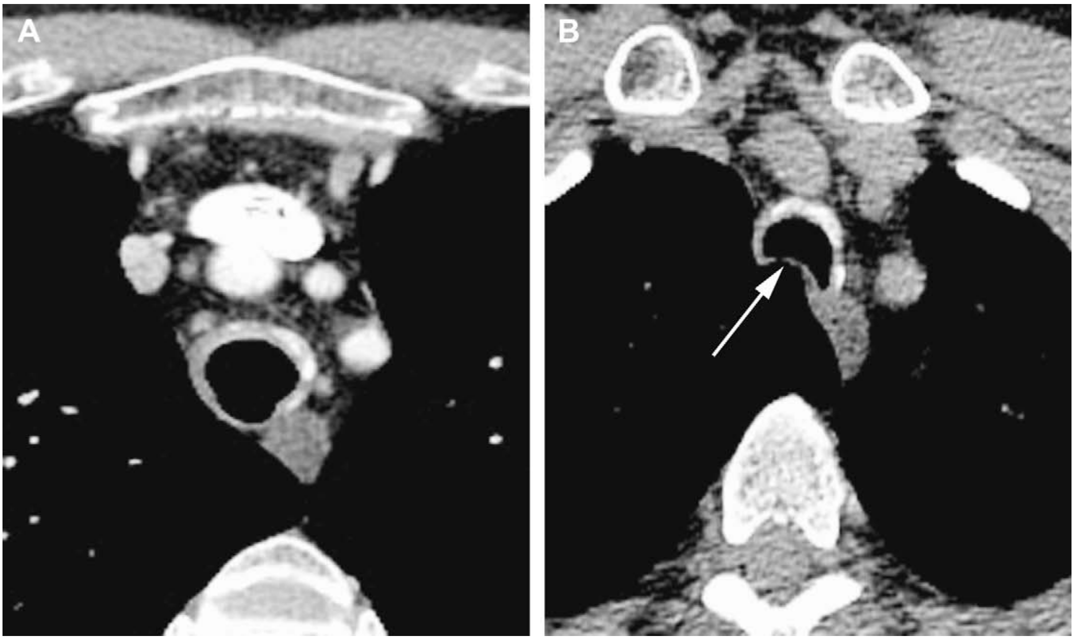

Fig. 5. TM in a 50-year-old woman with relapsing polychondritis presenting with intractable cough and dyspnea. End-inspiratory (*A*) and dynamic-expiratory (*B*) axial images of the upper trachea show calcified wall thickening with characteristic sparing of posterior membranous trachea. Excessive expiratory collapse of the trachea (*arrow*) is consistent with TM.

When interpreting functional CT scans of patients with TM, it is important to report the severity, distribution, and morphology. These factors have an important impact on treatment decisions, which are based on a combination of symptoms, severity and distribution of disease, and underlying cause of TM.[23]

Because there is not a single widely accepted scale for reporting the severity of TM, it is important to report the quantitative degree of

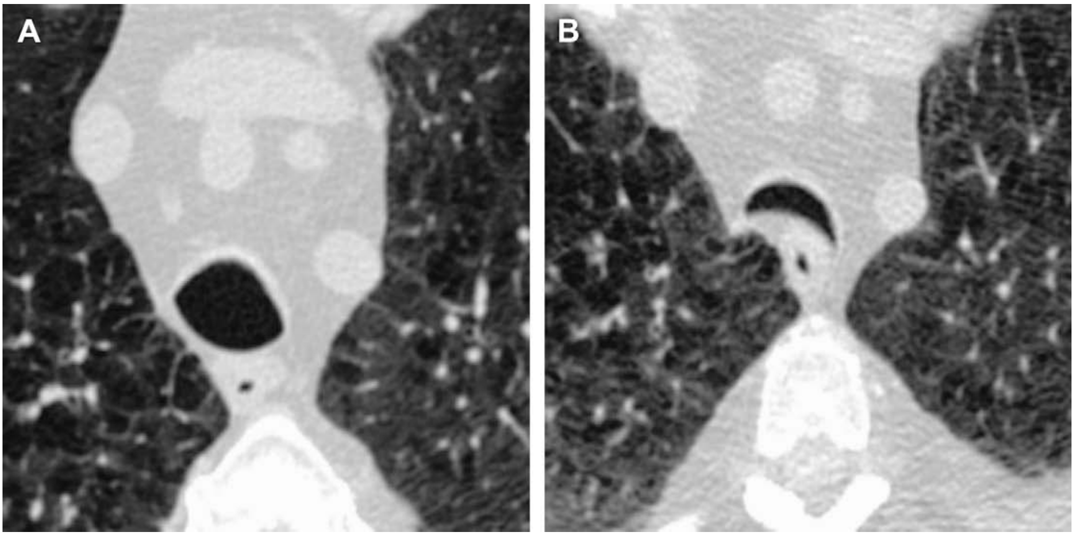

Fig. 6. Lunate configuration of the trachea in a 71-year-old woman with chronic cough and dyspnea. End-inspiratory CT image (*A*) demonstrates widening of coronal diameter of trachea with respect to the sagittal diameter, consistent with a lunate configuration. Dynamic-expiratory CT image (*B*) shows excessive expiratory collapse of airway lumen, consistent with TM.

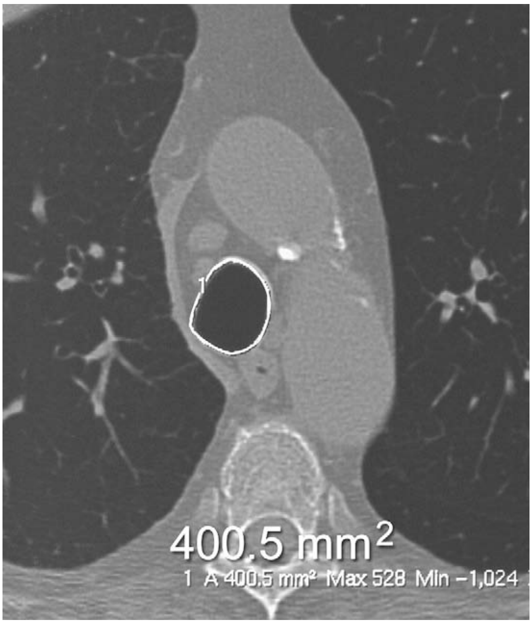

Fig. 7. Example of electronic tracing method for measuring cross-sectional area of tracheal lumen at the level of the aortic arch. The tracing line has been electronically thickened to enhance visibility for photographic reproduction. (*Reprinted from* Baroni RH, Feller-Kopman D, Nishino M, et al. Tracheobronchomalacia: comparison between end-expiratory and dynamic expiratory CT for evaluation of central airway collapse. Radiology 2005;235(2): 635–41; with permission.)

collapsibility rather than simply using a qualitative descriptor. A severity scale that has been used by some investigators includes three grades of severity based on the degree of airway collapse: (1) mild: 50% to 74%; (2) moderate: 74% to 99%; and (3) severe: 100% collapse.[7,23] In contrast, we consider more than 90% expiratory collapse as indicative of severe TM.

Murgu and Colt[23] recently proposed a functional class/extent/morphology/origin/severity (FEMOS) classification for TM. In this classification, a focal distribution of malacia is defined as involvement of one tracheal region (upper, middle, or lower) or involvement of one main or lobar bronchus. Multifocal distribution is defined as involvement of two contiguous or at least two noncontiguous regions, and diffuse involvement is defined as involvement of more than two contiguous regions. From a practical perspective, accurate determination of distribution has implications for treatment. For example, focal areas of malacia may benefit from stenting, whereas diffuse disease is more amenable to tracheoplasty surgery.

Regarding morphology, one should describe whether the collapse occurs circumferentially, or

Fig. 8. "Frown sign" of TM in 64-year-old man with chronic cough. Dynamic expiratory CT image demonstrates excessive collapse of trachea with crescenteric, "frown-like" configuration of airway lumen (*arrow*), consistent with TM.

if it occurs primarily because of either excessive bulging of the posterior membranous wall or collapse of the anterolateral cartilaginous structures. For example, patients with collapse primarily because of bulging and flaccidity of the posterior membranous wall are potential candidates for tracheoplasty surgery, a novel surgical technique in which in the posterior wall of the trachea is reinforced by a Marlex graft.[24] Surgical reinforcement of the posterior membranous wall enhances the rigidity of this structure and makes it less susceptible to bowing during expiration.

PREOPERATIVE AND POSTOPERATIVE ASSESSMENT

CT plays several potentially important roles in evaluating severely symptomatic TM patients who are undergoing evaluation for curative tracheoplasty surgery.[24] Preoperative roles include (1) precise characterization of airway shape and determination of which parts of the airway wall contribute to excessive airway collapsibility; (2) evaluation for systemic diseases such as relapsing polychondritis that are not amenable to surgical therapy; (3) identification of extrinsic, paratracheal masses that may alter surgical planning; and (4) baseline measure of airway collapsibility by which to compare postoperative scans for evaluating response to surgery. In the postoperative setting, CT provides a noninvasive method for assessing for postoperative complications and noninvasively quantifying the degree of improvement in airway collapsibility.

Our surgeons and pulmonologists have found a combination of subjective symptomatic improvement and quantitative reduction in airway collapsibility at CT to be the most helpful measurements of determining response to surgery.[24] Our preliminary findings comparing preoperative and postoperative scans showed that tracheoplasty resulted in a decrease in the degree of airway collapse that was accompanied by a qualitative improvement of respiratory symptoms.[24]

SUMMARY

TBM refers to excessive expiratory collapse of the trachea and bronchi as a result of weakening of the airway walls and/or supporting cartilage. This disorder has recently been increasingly recognized as an important cause of chronic respiratory symptoms. MDCT technology allows for noninvasive imaging of TBM with similar accuracy to the historical reference standard of bronchoscopy. Paired end-inspiratory, dynamic expiratory MDCT is the examination of choice for assessing patients with suspected TBM. Radiologists should become familiar with imaging protocols and interpretation techniques to accurately diagnose this condition using MDCT.

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