Tracheobronchomalacia in Infants and Children: Multidetector CT Evaluation

Edward Y. Lee, MD, MPH
Phillip M. Boiselle, MD

Tracheobronchomalacia (TBM) is the most common congenital central airway anomaly, but it frequently goes unrecognized or is misdiagnosed as other respiratory conditions such as asthma. Recent advances in multidetector computed tomography (CT) have enhanced the ability to noninvasively diagnose TBM with the potential to reduce the morbidity and mortality associated with this condition. Precise indications are evolving but may include symptomatic pediatric patients with known risk factors for TBM and patients with otherwise unexplained impaired exercise tolerance; recurrent lower airways infection; and therapy-resistant, irreversible, and/or atypical asthma. With multidetector CT, radiologists can now perform objective and quantitative assessment of TBM with accuracy similar to that of bronchoscopy, the reference standard for diagnosing this condition. Multidetector CT enables a comprehensive evaluation of pediatric patients suspected of having TBM by facilitating accurate diagnosis, determining the extent and degree of disease, identifying predisposing conditions, and providing objective pre- and postoperative assessments. In this article, the authors present a step-by-step primer of multidetector CT imaging for evaluating infants and children with suspected TBM, including clinical indications, patient preparation, multidetector CT techniques and protocols, two- and three-dimensional processing of multidetector CT data, and image interpretation. The major aim of this article is to facilitate the reader’s ability to successfully employ multidetector CT imaging protocols for evaluation of TBM in infants and children in daily clinical practice.

© RSNA, 2009

Supplemental material: http://radiology.rsna.org/cgi/content/full/252/1/7/DC1
Tracheobronchomalacia (TBM) is the most common congenital anomaly of the central airways (1). It arises from a weakness of the tracheobronchial wall and supporting cartilage, which leads to increased compliance and excessive expiratory collapsibility of the trachea and bronchi (Fig 1) (2–4). In patients with TBM, the close juxtaposition of the airway walls during expiration frequently results in an intractable cough due to recurrent vibrations and irritation of the airway. In addition, abnormally increased flaccidity of the trachea and bronchi associated with TBM prevents normal clearance of secretions and may lead to recurrent infections and bronchiectasis (5,6). If untreated, this condition may rarely be fatal (4).

Although TBM has recently been increasingly recognized as an important chronic respiratory illness associated with substantial morbidity in infants and children, it remains a relatively underdiagnosed condition because it generally escapes detection at routine imaging studies performed at end inspiration (5). Thus, affected patients may remain undiagnosed despite having undergone conventional radiography and computed tomographic (CT) scanning. Dedicated expiratory imaging is required to detect the excessive airway collapsibility that is diagnostic of this condition (5,7). Because our experience has shown that many radiologists are unfamiliar with expiratory techniques in pediatric patients, there is a need for a practical review of these methods.

This article provides a step-by-step primer of multidetector CT imaging for evaluating infants and children with suspected TBM, including clinical indications, patient preparation, multidetector CT techniques and protocols, two-dimensional and three-dimensional (3D) processing of multidetector CT data, and image interpretation. The major aim of this article is to facilitate the reader’s ability to successfully employ imaging protocols for evaluation of TBM in daily clinical practice.

Pathophysiology of TBM

To understand the underlying physiologic principles related to these protocols, 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 (4,10,11). Pleural pressure, which primarily depends on respiratory muscles, is elevated during expiratory efforts. On the other hand, intraluminal pressures, which mostly depend on airflow, are markedly variable. When there is no airflow, intraluminal pressure is the same as alveolar pressure and differs from pleural pressure only by the elastic recoil pressure of the lung, which depends on lung volume (10,11). At end inspiration (maximal lung volume with no airflow), the intraluminal pressure inside the airways is greater than pleural pressure by approximately 20–30 cm H₂O (10,11). This pressure difference expands the trachea. In contrast, at end inspiration, pleural pressure is markedly reduced by the lung elastic recoil which is most significant when there is no airflow. Because pleural pressure is less than alveolar pressure, there is a positive pressure difference that results in closing of small airways. This pressure difference is less in children with TBM due to their less compliant airways and consistent with the clinical presentation of wheezing in these patients (4,10). In addition, because the intrapleural pressure is lower during inspiration, there is less inspiratory tension that could cause further collapse of the airway. This concept is important for understanding why high-flow oxygen and high-frequency jet ventilation are used to maintain airway patency in patients with TBM (10,11).
expiration (low lung volumes with no airflow), the trachea is unstressed since intraluminal pressure is almost equal to pleural pressure. The trachea becomes most compressed during dynamic expiration and cough at low lung volume, when pleural pressure is highly elevated (approximately 100 cm H$_2$O) and transmission of the high alveolar pressures to the central airways is prevented by the expiratory flow limitation in the small airways (10,11). In these situations, intraluminal pressure is almost equal to atmospheric pressure, and the large transmural pressure results in tracheal collapse (10–12). Thus, because they result in higher intrathoracic (pleural) pressures, and the large transmural pressure results in tracheal collapse (10–12). Thus, because they result in higher intrathoracic (pleural) pressures, dynamic expiratory and coughing maneuvers are generally more sensitive for detecting malacia than end-expiratory maneuvers. Second, there is a paucity of information regarding the normal range of central airway collapse among pediatric patients of varying ages, ethnicities, and both sexes, both with and without coexisting pulmonary disease. It is known that there is overlap in the degree of tracheal collapsibility between healthy adult volunteers and adults with TBM (14). We anticipate that there is also overlap in the pediatric population. Thus, results in the low range of abnormal (50%–60% collapse) should be interpreted cautiously and correlated closely with pulmonary function testing results and clinical history and/or risk factors.

### Clinical Indications

Clinical symptoms associated with TBM in infants and children are typically nonspecific and varied, as summarized in Table 2. However, the most commonly reported symptoms associated with TBM are expiratory stridor and cough, often described as barking or brassy (4). Such symptoms should raise a high clinical suspicion for TBM. Paratracheal mediastinal vascular anomalies, including vascular rings and innominate artery compression, are frequently associated with focal TM at the level of extrinsic compression of the airway (15–17). In patients with both extrinsic compression and malacia, surgical correction of mediastinal vascular anomalies alone may not adequately treat the respiratory symptoms; thus, it is important to routinely assess for concomitant TM when imaging symptomatic patients known to have or suspected of having mediastinal vascular anomalies (15–17).

### Complexities and Uncertainties regarding Diagnosis of TBM

Although in some cases of pediatric TBM the diagnosis is clear-cut and made with confidence, there are many instances in which the diagnosis is complex and uncertain. Two major factors contribute to this complexity in the pediatric population. First, diagnosing TBM in infants and children on clinical grounds is challenging because clinical symptoms are often nonspecific and may be absent in some cases (4,13). For example, the challenge of diagnosing TBM in pediatric patients on clinical grounds has been recently reported by Boogaard et al (13). In their retrospective review of bronchoscopy performed in a series of 160 pediatric patients ages 0–17 years, these investigators reported that airway malacia was unsuspected clinically in roughly one-half of these patients with this condition. Most of these pediatric patients were initially misdiagnosed clinically as having asthma, with a subsequent delay in the accurate diagnosis of TBM. These authors emphasize the importance of assessing for TBM in pediatric patients with a history of impaired exercise tolerance, recurrent lower airways infection, and therapy-resistant, irreversible, and/or atypical asthma.
Although precise indications are evolving and established clinical guidelines are not currently available to our knowledge, evaluation for TBM is generally indicated for symptomatic pediatric patients with known risk factors for TBM, as outlined in Table 1 (4,5,18). As previously noted, evaluation for TBM may also be appropriate for patients with otherwise unexplained impaired exercise tolerance, recurrent lower airways infection, and therapy-resistant, irreversible, and/or atypical asthma (13). Although pulmonary function testing is nonspecific and rarely diagnostic, a characteristic flattening of the expiratory limb of the flow-volume loop may support a diagnosis of suspected TBM (19).

**Patient Preparation**

To correctly diagnose TBM with multidetector CT, diagnostic quality end-inspiratory and expiratory CT image data sets must be obtained. Successful scanning depends on the patients’ ability to follow breathing instructions for the inspiratory and expiratory phases of the multidetector CT examination. In general, the type of expiratory scanning is guided by the age of the child. As detailed in the following paragraphs, we have found that children 5 years of age or older can usually cooperate with breathing instructions for this examination, whereas those younger than 5 years of age generally require a controlled ventilation technique following intubation. Figure 2 shows an algorithm for preparing infants and children for evaluation of TBM with multidetector CT.

**Older Children**

Older children (>5 years old) are generally able to follow breathing instructions for the inspiratory and expiratory phases of the multidetector CT examination and ideally should practice breathing instructions in advance of the scan. To obtain the best-quality CT images, we first place the child in a comfortable supine position on the scanner table and then stabilize the head and neck, which helps limit patient motion during the examination (Fig 3).

CT technologists, who are familiar with multidetector CT techniques and

---

**Table 1**

<table>
<thead>
<tr>
<th>Disease (congenital)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal infants (idiopathic or primary TM proper)</td>
<td>Prematurity</td>
</tr>
<tr>
<td>Pulsatile collapse with normal innominate artery</td>
<td>Congenital abnormalities of the cartilage</td>
</tr>
<tr>
<td>Congenital syndromes associated with TM/TBM</td>
<td>Dyschondroplasia/chondromalacia/chondrodysplasia</td>
</tr>
<tr>
<td>Polychondritis</td>
<td>Ehlers-Danlos syndrome</td>
</tr>
<tr>
<td>Ehlers-Danlos syndrome</td>
<td>Mucopolysaccharidosis</td>
</tr>
<tr>
<td>Congenital syndromes associated with TM/TBM</td>
<td>Hunter syndrome</td>
</tr>
<tr>
<td>Hunter syndrome</td>
<td>CHARGE syndrome</td>
</tr>
<tr>
<td>WATER anomaly</td>
<td>Trisomy 9</td>
</tr>
<tr>
<td>Trisomy 21</td>
<td>Atelosteogenesis type 1</td>
</tr>
<tr>
<td>Antley-Bixler syndrome</td>
<td>11p13 deletion</td>
</tr>
<tr>
<td>22q11 deletion</td>
<td>18–22 translocation</td>
</tr>
<tr>
<td>Hallermann-Streiff syndrome</td>
<td>Pfeiffer syndrome</td>
</tr>
<tr>
<td>Blackfan-Diamond syndrome</td>
<td>Williams-Campbell syndrome</td>
</tr>
<tr>
<td>Kniest dysplasia</td>
<td>DiGeorge syndrome</td>
</tr>
<tr>
<td>Deletion of 12q</td>
<td>Larsen syndrome and Larsen-like syndromes</td>
</tr>
<tr>
<td>Brachmann-de Lange syndrome</td>
<td>Camptomelic dysplasia</td>
</tr>
<tr>
<td>Pierre-Robin syndrome</td>
<td>Congenital anomalies associated with TM/TBM</td>
</tr>
<tr>
<td>Tracheoesophageal fistula</td>
<td>Tracheoepiophageal fistula</td>
</tr>
<tr>
<td>EA with or without laryngeal cleft</td>
<td>Bronchopulmonary dysplasia</td>
</tr>
<tr>
<td>Tetralogy of Fallot with absent pulmonary valve</td>
<td>(Table 1 continues)</td>
</tr>
</tbody>
</table>

---

**Secondary (acquired)**

| Prolonged intubation                                                                 |
| Tracheotomy                                                                        |
| Severe tracheobronchitis                                                           |
| Resulting from compression                                                        |

**Vascular**

| Double aortic arch                                                                 |
| Abnormal take-off of the innominate artery                                         |
| Anomaly of left pulmonary artery                                                   |
| Right aortic arch                                                                  |
| Aberrant right subclavian                                                          |
| Enlarged pulmonary veins                                                           |

**Cardiac**

| Left atrial hypertrophy                                                           |
| Enlarged left atrium                                                              |

**Skeletal**

| Scoliosis                                                                         |
have been trained in breathing instructions for this protocol, can assist older children in practicing proper breathing techniques for the inspiratory and expiratory phases of the study. By explaining the procedure to an older child at a level he or she can understand, the overall success of the procedure is ensured. A script of breathing instructions for this study is provided in Appendix E1 (http://radiology.rsna.org/cgi/content/full/252/1/7/DC1) (20). For cine multidetector CT combined with a coughing maneuver, the radiologist and/or CT technologist may assist older children in practicing coughing techniques by asking the child to perform repetitive coughs in a supine position in the CT scanner while limiting neck and chest movement. The latter is important in order to prevent motion artifacts.

Infants and Young Children

Infants and children 5 years of age and younger usually require general anesthetic and intubation in order to apply a controlled ventilation technique (breath holding) that is requisite to performing end-inspiratory and expiratory phases of the multidetector CT examination (discussed in detail in the following section of this article) (16,17).

Sedation and Intubation

At our institution, a team consisting of pediatric radiologists, pediatric anesthesiologists, sedation nurses, and CT technologists prepare sedation that is tailored (ie, type, strength, dose, duration) to the needs of each patient in advance of a multidetector CT examination. Such preparation helps to ensure a successful study that yields useful diagnostic information.

Pediatric anesthesiologists and sedation nurses perform a presedation evaluation on all infants and young children being considered for examination with multidetector CT for suspected TBM. Only infants and young children who pass the evaluation will be approved for sedation. At our institution, intravenously administered propofol is the sedative agent most often selected for general anesthesia in infants and young children. Once the patients are adequately sedated and securely placed in the supine position on the CT table, the pediatric anesthesiologist intubates the patient by using an endotracheal tube. In infants and young children with a known or suspected tracheal obstruction (above the thoracic inlet level) due to underlying stenosis or intraluminal mass, a securely positioned face mask can be used instead of an endotracheal tube.

Throughout the sedation procedure and sedation recovery period, a pediatric anesthesiologist and an experienced sedation nurse closely monitor the patient’s respiratory rate, heart rate and rhythm, and blood oxygen saturation levels by using a transcutaneous pulse oximeter and blood pressure cuffs to decrease the potential risk of sedation-related complications.

Intravenous Contrast Material

Intravenous contrast material is unnecessary for the routine assessment of TBM (21,22). However, it should be considered in certain settings, including known or suspected mediastinal vascular anomalies (ie, innominate artery compression, vascular rings, and pulmonary artery sling), extrinsic mediastinal masses (eg, foregut duplication cyst, lymphadenopathy), or central airway neoplasms (21–23).

Contrast material type and dose.—Nonionic contrast medium is the choice for intravenous contrast material. The contrast material dose is 2 mL per kilogram of patient body weight (not to exceed 4 mL/kg or a total amount of 125 mL) (21–23).

Contrast material injection methods.—There are two methods of administering intravenous contrast material

---

### Table 1 (continued)

<table>
<thead>
<tr>
<th>Disease</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tumors and cysts</td>
<td></td>
</tr>
<tr>
<td>Teratomas</td>
<td></td>
</tr>
<tr>
<td>Cystic hygromas</td>
<td></td>
</tr>
<tr>
<td>Hemangiomas</td>
<td></td>
</tr>
<tr>
<td>Bronchogenic cysts</td>
<td></td>
</tr>
<tr>
<td>Enterogenic cysts</td>
<td></td>
</tr>
<tr>
<td>Thymoma</td>
<td></td>
</tr>
<tr>
<td>Thymus enlargement</td>
<td></td>
</tr>
<tr>
<td>Goiter</td>
<td></td>
</tr>
<tr>
<td>Lymphatic malformation</td>
<td></td>
</tr>
<tr>
<td>Lymphoma</td>
<td></td>
</tr>
<tr>
<td>Neuroblastoma</td>
<td></td>
</tr>
<tr>
<td>Infection</td>
<td></td>
</tr>
<tr>
<td>Abscess</td>
<td></td>
</tr>
<tr>
<td>Posttraumatic</td>
<td></td>
</tr>
</tbody>
</table>

Note.—CHARGE = colobomatous of the eyes, heart defects, chondal atresia, retardation of growth, genital hypoplasia, and ear abnormalities; EA = esophageal atresia; VATER = vertebral defect, anal atresia, tracheoesophageal fistula, esophageal fistula, and radial/renal dysplasia. Reprinted, with permission, from reference 4.

### Table 2

<table>
<thead>
<tr>
<th>Symptoms of Pediatric Tracheomalacia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stridor</td>
</tr>
<tr>
<td>Barking cough</td>
</tr>
<tr>
<td>Respiratory distress</td>
</tr>
<tr>
<td>Wheeze</td>
</tr>
<tr>
<td>Anoxic spells</td>
</tr>
<tr>
<td>Cyanosis</td>
</tr>
<tr>
<td>Bradycardia</td>
</tr>
<tr>
<td>Tachyarrhythmias</td>
</tr>
<tr>
<td>Spontaneous hyperextension of the neck</td>
</tr>
<tr>
<td>Prolonged expiratory phase</td>
</tr>
<tr>
<td>Breathholding spells</td>
</tr>
<tr>
<td>Failure to thrive</td>
</tr>
<tr>
<td>Increased work of breathing</td>
</tr>
<tr>
<td>Ecternal, substernal, and intercostal retractions</td>
</tr>
<tr>
<td>Recurrent pulmonary infections</td>
</tr>
<tr>
<td>Reflex apnea</td>
</tr>
<tr>
<td>Respiratory arrest</td>
</tr>
<tr>
<td>Cardiac arrest</td>
</tr>
</tbody>
</table>

Note.—Reprinted, with permission, from reference 4.
HOW I DO IT: Multidetector CT of Tracheobronchomalacia in Infants and Children

Lee and Boiselle

Figure 2

Figure 2: Algorithm for preparing infants and children for evaluation of TBM at multidetector CT. Chest radiography (CXR), which can usually depict lung parenchymal causes (eg, pneumonia, congenital lung anomalies) is usually the initial modality for evaluating infants and children with respiratory distress. For those suspected of having central airway abnormalities on the basis of clinical symptoms and/or chest radiography findings, bronchoscopy is typically next in case of foreign body aspiration, while multidetector CT is a useful noninvasive modality in case of suspected TBM or stenosis. Infants and young children (≤5 years old) generally cannot follow breathing instructions for inspiratory and expiratory phases and require general anesthetic and intubation. In infants and young children with a known or suspected tracheal obstruction (above thoracic inlet level), a securely positioned face mask can be used instead of an endotracheal (ET) tube. Older children (≥5 years old), who can generally follow breathing instructions, ideally should receive instruction in breathing techniques and be allowed to practice in advance. While global or focal evaluation of central airway malacia can be evaluated with inspiratory and expiratory CT, cine CT with a coughing maneuver can assess a focal central airway malacia with increased diagnostic sensitivity. In patients with suspected concurrent mediastinal vascular anomalies or central airway neoplasm, intravenous (IV) contrast material can be administered during inspiratory phase scanning. Once proper CT data sets are obtained, visual and quantitative evaluation of axial, two-dimensional (2D), and 3D images can be performed at picture archiving and communication system (PACS) and CT workstations. During a CT examination—hand injection and mechanical injection, the choice of which depends on the size of the intravenous catheter and the stability of intravenous catheter placement (21–23). In patients with a secure 22-gauge or larger catheter in an antecubital vein, mechanical injection is the method of choice (22,23). In infants and young children with a small-caliber catheter (<22 gauge) or a central access line, we recommend intravenous injection of contrast material by hand, by using a bolus technique (16,17,23,24). Although the preferred location of an intravenous catheter is an antecubital vein, smaller veins on the hand or foot of infants and young children are also suitable. If the intravenous catheter is securely positioned and properly functioning, the complication rates for manual and mechanical injections are similar (<0.4%) (25). However, whenever possible, mechanical injection of the intravenous contrast material is the preferred method instead of hand injection since it provides more homogeneous contrast material enhancement within the vessels, which is particularly helpful for 3D imaging (21–23).

Multidetector CT Techniques

Types of CT Techniques for Evaluation of TBM

Evaluation of TBM generally requires that the patient be imaged during both the inspiratory and expiratory phases of the respiratory cycle (3,7). In our practice, we rely primarily on two main types of multidetector CT techniques: (a) paired end-inspiratory and end-expiratory multidetector CT, and (b) paired end-inspiratory and dynamic expiratory multidetector CT. Additionally, cine multidetector CT combined with a coughing maneuver is an alternative technique that may be helpful for imaging patients with focal TBM. Previously published data in adult patients support the increased sensitivity of diagnosing TBM with dynamic expiratory multidetector CT rather than end-expiratory multidetector CT (10).
Thus, in children 5 years of age or older with suspected TBM who can follow breathing directions, the dynamic expiratory multidetector CT technique should be performed. However, although less desirable, end-expiratory maneuvers are sufficient for evaluating TBM in infants and young children who require intubation and controlled ventilation (15,16). As discussed in the “Patient Preparation” section of this article, the decision as to which method to employ is dependent on the patient’s ability to cooperate with respiratory instructions.

**Paired end-inspiratory/end-expiratory and paired end-inspiratory/dynamic expiratory CT.**—The end-inspiratory phase of imaging is the same for both protocols, but the type of expiratory imaging differs. Whereas images are obtained at the end of exhalation in end-expiratory multidetector CT, they are acquired during a forced exhalation in dynamic expiratory multidetector CT.

In infants and young children who require general anesthetic and intubation, end-inspiratory and end-expiratory phases of CT scanning are performed by alternatively applying and withholding positive pressure ventilation during inspiration and expiration, respectively (16,17). To approximate the level of end-inspiratory pressure that is typically generated by nonintubated children, the end-inspiratory pressure in sedated and intubated infants and young children should be held at 20 cm H$_2$O. Maintaining consistent pressure at this level throughout the end-inspiratory phase of CT scanning prevents the airways from artificially expanding below or beyond the normal physiologic range. After end-inspiratory phase CT scanning, the positive pressure ventilation is withheld, which results in an end-expiratory pressure close to 0 cm H$_2$O. With breath-hold technique at this level, end-expiratory phase CT scanning is performed, which typically takes less than 5 seconds. Immediately after the completion of end-expiratory CT scanning, standard ventilation by means of an endotracheal tube is reinitiated.

**Cine CT combined with a coughing maneuver.**—With the recent development of 64 detector CT, which provides high spatial and temporal resolution combined with greater anatomic coverage, cine imaging of the central airways during respiratory maneuvers for the detection of TBM is now possible. During a single cine acquisition with 64-detector CT, anatomic coverage up to 4 cm in the z-axis can be obtained (26). This technique can be used with both dynamic breathing and a coughing maneuver. However, because coughing elicits a higher level of intrathoracic–extratracheobronchial pressure than does end exhalation or forced exhalation, it is the preferred respiratory maneuver for cine imaging (26).

**Multidetector CT Parameters**

The acquisition of an optimal multidetector CT data set is based on selecting proper multidetector CT parameters in advance of the study, including tube current or milliamperage, kilovoltage peak, table speed, detector collimation, and reconstruction thickness (for 3D reconstruction) (21–23).

Achieving an optimal and safe radiation dose is a particularly important consideration in imaging infants and children, who are more susceptible than adults to the potentially harmful effects of ionizing radiation (27–30). The amount of radiation depends on milliamperage and kilovoltage peak, which should be set as low as possible (following an ALARA [as low as reasonably achievable] principle) while maintaining the diagnostic quality of CT (21–23,27–30). Furthermore, employing z-axis modulation, which acquires images at a user-specified image noise level with reduced tube current–time product, can further decrease the radiation dose (31). In general, due to the inherently high contrast between the air-filled tracheal lumen and adjacent soft-tissue attenuation of the mediastinum, milliamperage can be reduced without negatively affecting the diagnostic capability of multidetector CT in evaluating TBM (32–35).

One disadvantage of dual-phase (ie, inspiratory and expiratory phase) multidetector CT imaging, however, is the potential for using twice as much radiation than is typically used in a single-phase acquisition. To offset this potential drawback, ionizing radiation exposure can be minimized during a multidetector CT study by decreasing the milliamperage during the expiratory phase of multidetector CT studies (32–35). This is readily achievable because the central airways and small
airways disease are well assessed at reduced-dose CT (35,36). In contrast, a standard-dose technique should be employed for the end-inspiratory scan, which is used for comprehensive anatomic assessment of the airways and lungs.

The estimated effective radiation dose from paired inspiratory and expiratory multidetector CT typically ranges between 3.5 and 7.5 mSv. This variability reflects differences in patient factors, length of acquisitions, and scanner configurations.

### Technical Considerations

**Paired end-inspiratory/end-expiratory and paired end-inspiratory/dynamic expiratory CT.**—In general, the guidelines for calculating milliampere and kilovoltage peak are based on patient weight as listed in Table 3, which is applicable to most available multidetector CT scanners (more than four rows). To decrease ionizing radiation, low-dose techniques (approximately one-half of milliampere used for the end-inspiratory phase) can be used during expiratory phase of the multidetector CT study without compromising diagnostic image quality (32–35). To ensure a rapid CT acquisition, we recommend using a gantry rotation time of 1 second or less and a pitch of 1.0–1.5, which are available on most multidetector CT scanners (more than four rows) (21–23). Detector collimation varies based on the type of multidetector CT scanner. In general, however, 1.0–1.5-mm collimation with a pitch of 1.5–2.0 for four-row multidetector CT, 0.625–1.0-mm collimation with a pitch of 1.0–2.0 for eight- to 16-row multidetector CT, and 0.5–0.6-mm collimation with a pitch of 1.0–1.5 for 64-row multidetector CT will be sufficient to achieve optimal image quality (21–23). With collimation thickness greater than 1.0 mm, a reconstruction interval should be selected that provides approximately 50% overlap to enhance the quality of reconstruction images and to prevent artifacts (37–39). Three-dimensional volumetric CT data can be sufficiently reconstructed with a 3-mm section thickness at a 2-mm reconstruction interval or with a 2-mm section thickness at a 1-mm reconstruction interval. An advantage of a very thin collimation (0.5–1.0 mm) with a higher number of detector rows (more than four) is that it results in an isotropic data set, where spatial resolution is the same when images are reviewed in transverse and multiplanar axes (eg, sagittal and coronal planes), thus obviating the need for overlapping reconstruction intervals (40).

**Cine CT combined with a coughing maneuver.**—With 64-row multidetector CT, the following parameters should ideally be used for a cine CT study for evaluating TBM: weight-based milliampere and kilovoltage peak (Table 3); gantry rotation, 0.5 second or less; and detector collimation, 0.5–0.625 mm (26). The use of a low-dose technique (approximately one-half of milliampere used for end-inspiratory phase) has been previously validated (35). Images are reconstructed at 8-mm collimation in a standard algorithm, creating four contiguous cine data sets from a single acquisition.

### Table 3

<table>
<thead>
<tr>
<th>Weight (kg)</th>
<th>Tube Current at Inspiration/Expiration (mAs)</th>
<th>Kilovoltage (kVp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>40/20</td>
<td>80</td>
</tr>
<tr>
<td>10–14</td>
<td>50/25</td>
<td>80</td>
</tr>
<tr>
<td>15–24</td>
<td>60/30</td>
<td>80</td>
</tr>
<tr>
<td>25–34</td>
<td>70/35</td>
<td>80</td>
</tr>
<tr>
<td>35–44</td>
<td>80/40</td>
<td>80</td>
</tr>
<tr>
<td>45–54</td>
<td>90/40</td>
<td>90</td>
</tr>
<tr>
<td>55–70</td>
<td>100–120/40</td>
<td>100–120</td>
</tr>
</tbody>
</table>

Note.—For tube current and kilovoltage by patient weight for the end-inspiratory examination, tube current should be reduced by 50% to a maximum of 40 mAs while maintaining the same level of kilovoltage for the end-inspiratory examination.

**Anatomic Scan Coverage**

**Paired end-inspiratory/end-expiratory and paired end-inspiratory/dynamic expiratory CT.**—The determination of the area of coverage (and assessment of the location of an endotracheal tube in infants and young children who are intubated) can be made on an initial scout topographic image of the CT study. For infants and young children, the tip of the endotracheal tube should be placed just above the thoracic inlet, thus securing its position and allowing for assessment of the intrathoracic central airway.

CT scans are acquired from just below the vocal cords to 3 cm below the level of the carina, effectively capturing the entire central airway with both paired end-inspiratory and end-expiratory multidetector CT or paired end-inspiratory and dynamic expiratory multidetector CT. Volumetric imaging ensures comprehensive scanning of all of the central airways, thus minimizing the possibility that a focal area of malacia might be overlooked (4,19). In patients undergoing their first chest CT examination without an established diagnosis of TBM, it is reasonable to extend the scanning acquisition to the diaphragm in order to provide a comprehensive assessment of both large and small airways. However, to minimize radiation exposure, a more limited acquisition is recommended for those patients with established diagnoses of TBM and those with a recent chest CT scan that includes the entirety of the lungs.

**Cine CT combined with a coughing maneuver.**—When cine multidetector CT is combined with a coughing maneuver, the region of interest for TBM is selected based on initial scout topographic images covering approximately 3.2–4 cm (0.625-mm detector width × 64 detectors, or 0.5 mm × 64, depending on the manufacturer) in craniocaudal length during a single cine acquisition with 64-detector CT (26). Such a focused technique is best suited for patients with a known extrinsic paratracheal mass or mediastinal vascular anomalies. To “sample” the trachea and proximal main stem 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 approximately 4 cm above this level.
For greater coverage, two separate sets of multidetector CT scans can be obtained, which increase the total length of coverage by up to 8 cm (depending on the CT manufacturer). The recently introduced volumetric 320-detector CT scanner, which can provide up to 16 cm (0.5-mm detector width/320 detectors) of anatomic coverage in a single rotation (0.35 second per rotation), shows much promise for the evaluation of TBM because it can cover the entire central airway in infants and young children and the majority of the entire intrathoracic trachea in most older children.

**Scanning Order, Direction, and Initiation Time**

_Paired end-inspiratory/end-expiratory and paired end-inspiratory/dynamic expiratory CT._—The end-inspiratory phase scan is performed first, followed by the expiratory phase scan from cranial to caudal direction. To evaluate associated mediastinal vascular anomalies simultaneously, intravenous contrast material should be administered during the end-inspiratory phase of the study. When optimal contrast material enhancement is observed in the left ventricle by means of bolus tracking after administration of intravenous contrast material, scanning is initiated (16,17).

_Cine CT combined with a coughing maneuver._—For cine multidetector CT combined with a coughing maneuver, a 3-second acquisition is typically obtained in cine mode, beginning at end inspiration and followed by repeated coughing maneuvers (26).

**Postprocessing Technique**

One of the most beneficial advantages of multidetector CT is its ability to produce high-quality MPR and 3D images, which are now routinely used to evaluate patients with TBM (5,21,22,32,41–46).

**Multiplanar Reformation**

MPR images can be created along any selected planes such as coronal, sagittal, orthogonal, and curved planes (Fig 4) (21–23). For airway imaging, curved oblique reformations are particularly useful for tubular structures such as the trachea and bilateral main bronchi (21,22). While a curved coronal MPR is reconstructed by following a reference line though the center of the airway on sagittal images (Fig 4), a curved sagittal MPR is created by following a line thorough the center of the airway on coronal images. Such curved MPR images allow visualization of the central airway to be “straightened” so that the exact measurement can be obtained for a preoperative plan for surgery or interventional treatment. Although MPRs are easily and quickly created at the CT console or two-dimensional/3D workstation, they lack the anatomically meaningful “depth” of information that can be provided by 3D volumetric imaging (21–23).

**Three-dimensional Volume Rendering**

Volume-rendering, based on an edge detection image processing system, is the most widely used 3D reconstruction technique for the evaluation of central airways (21,22). With the 3D volume rendering technique, 3D images are created according to a preset threshold of CT attenuation using all of the CT information initially acquired. Visually accessible and anatomically meaningful interactive 3D images can be created in real time on the basis of preset thresholds from the initial CT data sets (21,22). Such 3D images can be applied to the preoperative planning for surgery or intervention.

**Figure 4**

Images in 5-year-old girl who presented with recurrent shortness of breath. The patient subsequently underwent multidetector CT, which showed normal central airways without evidence of TBM. (a) Coronal MPR soft-tissue window image of the central airways shows that the trachea (T) is not visualized in its entirety because it normally courses obliquely rather than parallel to the coronal axis. On this image, a portion of esophagus (E) is also visualized. (b) Sagittal MPR image shows a reference line through the center of the airway for reconstruction of a curved coronal MPR image. (c) Curved coronal MPR image demonstrates the entire trachea (T), in contrast to the coronal MPR image in a, where only a portion of trachea is visualized.
postprocessing techniques allow the initial data to be displayed in three dimensions from an external (ie, CT bronchography) or internal (ie, virtual bronchoscopy) perspective of the central airways (21,22). In the past, the principle limitation of 3D volume rendering has been the potentially time-consuming image reconstruction process. However, with the introduction of various preset airway reconstruction algorithms and commercial 3D software programs, this limitation has been virtually eliminated.

Image Interpretation: A Practical Systematic Central Airway Evaluation for TBM

In assessing for TBM, inspiratory and expiratory axial CT images must be carefully evaluated and compared at similar anatomic levels. In selected cases, MPR and 3D images may provide clinically relevant complementary information.

In evaluating the central airways, axial CT images provide an accurate assessment of (a) intrinsic tracheal size, shape, and wall thickness; (b) extraluminal abnormalities, such as extrinsic mediastinal masses or vascular anomalies; and (c) complications of malacia, such as bronchiectasis and air trapping (21,22,32,47).

Although axial images are the cornerstone of imaging evaluation of TBM, it is important to be aware that they may underestimate the craniocaudal extent of disease (5,41). This limitation can be effectively offset by combining axial images with MPR images. On the other hand, 3D reconstructions are useful for providing a comprehensive assessment of TM associated with mediastinal vascular anomalies or nonvascular paratracheal masses (21,22,32,47). Additionally, because the main bronchi course oblique to the axial plane, they are not ideally assessed on axial images. Thus, 3D volume rendering of the airways is helpful to evaluate for bronchomalacia.

Paired End-Inspiratory and End-Expiratory and Paired End-Inspiratory and Dynamic Expiratory CT

Evaluation of image quality.—To systematically evaluate paired end-inspiratory/end-expiratory and paired end-inspiratory/dynamic expiratory images for suspected TBM, axial CT image evaluation is begun by assessing the quality of inspiratory and expiratory CT data sets on a PACS workstation by using standard soft-tissue (level, 40 to 50 HU; width, 400 to 450 HU) and lung (level, −450 to −550 HU; width, 1600 to 1800 HU) window settings. The quality of both inspiratory- and expiratory-phase CT data sets should be carefully as-
sessed, as inadvertent imaging during submaximal inspiration or expiration can produce errors in airway measurement, which, in turn, may lead to misdiagnosis.

To ensure that multidetector CT acquisitions have been optimally performed during inspiration and expiration phases of the respiratory cycle, both CT technologists and radiologists should be familiar with the characteristics of diagnostic-quality inspiratory and expiratory scans. Features of a diagnostic inspiratory scan include a round or oval configuration of the trachea and well-expanded lungs (Fig 5). Features of a diagnostic expiratory scan include (a) flattening or anterior bowing of the posterior membranous wall of the trachea (Fig 5), (b) increased attenuation of the lung parenchyma, and (c) decreased overall lung volumes associated with decreased anteroposterior dimension of the chest (Fig 6) (32).

Visual evaluation of TBM.—Once the quality of the multidetector CT data set is ensured, the trachea and main bronchi should be carefully inspected on end-inspiratory phase images for contour, caliber, wall thickness, intraluminal mass (eg, neoplasm), and adjacent mediastinal soft tissue and vascular structures, which can cause extrinsic mass effects on central airways (5).

**Inspiratory CT images.—**At end inspiration, the normal appearance of the trachea is a round or oval (Fig 7) configuration. Horseshoe-shaped trachea (Fig 8), often associated with submaximal inspiratory effort, is also seen occasionally in normal subjects. Widening of the posterior membranous wall of the trachea (ie, a lunate configuration) has been described in patients with TBM on end-inspiratory phase images (5,48). For the majority of patients with TBM, however, the appearance of the trachea is generally normal. Because of the association between TM and tracheomegaly, the caliber of the trachea should also be carefully assessed (5), followed by an inspection of focal or diffuse wall thickening of the central airways. When evaluating the caliber of the trachea, close attention should be paid to the location and extent of tracheomegaly. Regions involved by tracheomegaly should be inspected carefully on expiratory CT images for the presence of concomitant TM. For determining the caliber of the trachea, published standard mean tracheal cross-sectional areas in normal pediatric population can be used for reference as listed in Figure 9 (49,50). Finally, intraluminal abnormalities (eg, central airway neoplasm, foreign body aspiration) and mediastinal abnormalities (eg, vascular rings and sling, lymphadenopathy) may produce intrinsic or extrinsic effects on the central airways, respectively (5,21,22,46,51). Because of their characteristic CT appearances on end-inspiratory images, these entities can generally be easily distinguished from TM.

**Expiratory CT images.—**After evaluating end-inspiratory CT images, the trachea and main bronchi should be carefully assessed for excessive collapse on CT images obtained at the end-expiratory phase or during dynamic exhalation (5).

Mild flattening or anterior bowing of the posterior wall of the central airways can normally be seen on expiratory-phase CT images in infants and children without malacia (Fig 5b). In contrast,
HOW I DO IT: Multidetector CT of Tracheobronchomalacia in Infants and Children

Lee and Boiselle

marked anterior bowing of the posterior membranous wall, which results in a frown-like or crescent appearance of the central airways owing to close proximity of the posterior and anterior walls, is typically detected in patients with TBM (5,44). However, concentric narrowing can be also seen, especially among patients with cartilaginous disorders (48).

The diagnosis of TBM can be confidently made on the basis of visual analysis of the images in the setting of near complete collapse of the airway lumen during expiration owing to severe malacia. However, the most accurate way to diagnose TBM (in the setting of incomplete collapse of the airway lumen) is to use an electronic tracing tool to quantitatively calculate the cross-sectional area of the airway lumen on images at the same anatomic level obtained on the images at inspiration and expiration (5).

Quantitative evaluation of TBM.—Quantitative assessment of the central airways can be performed by measuring the lumen of the central airways with a computerized tracing tool, which is available on most commercial PACS workstations (5,16,17). The cross-sectional area of the airway in square millimeters is calculated by hand-tracing the inner wall of the airway using an electronic tool available on PACS.

In calculating the luminal area of central airways for assessing TBM, emphasis should be placed on (a) obtaining measurements at similar anatomic levels during inspiration and expiration and (b) performing measurements on lung window images (eg, level, −450 to −550 HU; width, 1600 to 1800 HU) rather than soft-tissue window images because the interface between the airway lumen and airway wall is better defined with lung window settings than with soft-tissue window settings (5,16,17).

CT criterion of TBM.—The standard CT criterion of at least 50% expiratory reduction in the cross-sectional luminal area of the trachea or bronchi that is applied for diagnosing TBM is the same criterion applied to bronchoscopy (5,7,19). In children, this criterion is supported by a prior study by Wittenborg et al (52), who demonstrated that changes in the diameter of the trachea are minimal with quiet breathing and vary between 20% and 50% with exertional respiratory efforts such as crying or struggling. These findings are further supported by research by Newth et al (53) who showed that, based on direct observation during flexible bronchoscopy, the difference between maximal and minimal cross-sectional area of the trachea with respiration does not normally exceed 50% in pediatric patients. Although the diagnostic criterion of at least 50% reduction of the cross-sectional area of the trachea during expiration has been widely applied to CT studies, it is important to note that the use of end-expiratory imaging rather than dynamic expiratory imaging may require a lower threshold criterion for diagnosing TBM, due to the higher intrathoracic pressures generated by a dynamic expiratory maneuver resulting in increased tracheal collapse (10). To ensure that the diagnostic criterion for TBM is sufficiently robust, there is a need for collection of normative CT data in the pediatric population by using both of these expiratory methods. The equation for calculating percentage luminal collapse between inspiration and expiration is as follows: $100 \times \left[1 - \left(\frac{\text{luminal area of airway at end expiration}}{\text{luminal area of airway at end inspiration}}\right)\right]$. 

Distribution of TBM.—Central airway malacia can be isolated to either the trachea (TM) (Fig 1) or bronchi (bronchomalacia) (Fig 11) or may diffusely involve both the trachea and bronchi (TBM). When there is a fixed defect (ie, lack of caliber change within a narrowed segment of central airways
between inspiration and expiration), multidetector CT findings are consistent with central airway stenosis or stricture rather than malacia (Fig 12) (45). Once TBM is detected, its cranio-caudal extent (ie, focal vs diffuse) should be accurately determined because this parameter influences the method of treatment (5). For example, while stent placement is usually performed in patients with symptomatic focal TBM, tracheoplasty (reinforcement of the posterior wall of the airway with a graft) is the method of choice for patients with a long segment diffuse TM (5,54). In infants and children with TM associated with mediastinal vascular anomalies (particularly innominate artery compression syndrome), surgical resection in conjunction with aortopexy can be used to treat both mediastinal vascular anomalies and the underlying TM simultaneously (17,55–57).

Cine CT Combined with a Coughing Maneuver

The multidetector CT data are first transferred to either a PACS workstation or a 3D workstation for visual assessment. On a PACS or 3D workstation, the images can be reviewed in both a cine loop and freeze-frame fashion (26). The quality of CT data are checked for coverage of the intended area of interest and for the presence of motion artifacts involving the tracheal walls or lumen (eg, blurring or doubling of airway walls and lumen), which limits optimal evaluation (26).

For quantitative evaluation, a commercial software program (Analyze 6.0; Analyze Direct, Lenexa, Kan) is used at our institution for automated measurement of changes in the tracheal lumen cross-sectional area values during the cine sequence at either a PACS or a 3D workstation (26). TBM is defined according to standard criteria as 50% or more reduction in the cross-sectional area lumen during cine multidetector CT combined with a coughing maneuver. However, because coughing is a very forceful and provocative maneuver, it is likely that a higher threshold such as 60% or 70% may need to be employed to reduce the rate of false-positive diagnoses.

Treatment of TBM

Prompt and accurate diagnosis of TBM is important to prevent misdiagnosis or delayed diagnosis and to facilitate appropriate treatment. For example, because the therapeutic approach is fundamentally different for pediatric patients with TBM than for children with other respiratory conditions, a prompt diagnosis of TBM will prevent the prescription of unnecessary drugs to treat asthma or other respiratory disorders that may be clinically confused with this condition (13).

Treatment of TBM varies depending
on the age of the patient, the severity and distribution of malacia, the severity of symptoms, and the presence or absence of extrinsic airway compression from a vascular ring or mass. In many infants and young children with mild to moderate TBM, a conservative approach is the preferred method of initial management because the symptoms associated with TBM often resolve by age 1–2 years owing to strengthening and stiffening of the tracheal cartilage with normal growth and development (4,11,58–61). Conservative therapy includes treatment of respiratory infections, humidified oxygen therapy, and pulmonary physiotherapy (4,62,63).

For infants and children with more severe and progressive symptoms who do not recover spontaneously and are unresponsive to conservative management, there are several more aggressive treatment options currently available, including continuous positive airway pressure, tracheostomy placement, stent placement, and surgical intervention (4,54–69). In particular, surgical intervention is reserved for infants and children with recurrent pneumonia, intermittent respiratory obstruction, inability to extubate the airway, and dying spells (4,63,70–73). While stent placement may be considered as a temporary measure for patients with symptomatic, focal TBM, tracheoplasty (surgical reinforcement of the tracheal cartilage with normal growth owing to strengthening and stiffening of the tracheal cartilage with normal growth and development (4,11,58–61). Conservative therapy includes treatment of respiratory infections, humidified oxygen therapy, and pulmonary physiotherapy (4,62,63).

For infants and children with more severe and progressive symptoms who do not recover spontaneously and are unresponsive to conservative management, there are several more aggressive treatment options currently available, including continuous positive airway pressure, tracheostomy placement, stent placement, and surgical intervention (4,54–69). In particular, surgical intervention is reserved for infants and children with recurrent pneumonia, intermittent respiratory obstruction, inability to extubate the airway, and dying spells (4,63,70–73). While stent placement may be considered as a temporary measure for patients with symptomatic, focal TBM, tracheoplasty (surgical reinforcement of the tracheal cartilage with normal growth owing to strengthening and stiffening of the tracheal cartilage with normal growth and development (4,11,58–61). Conservative therapy includes treatment of respiratory infections, humidified oxygen therapy, and pulmonary physiotherapy (4,62,63).

Future Directions

Although paired inspiratory-expiratory imaging methods are the mainstay of imaging in pediatric patients with suspected TBM, recent advances in multidetector CT have paved the way for cine imaging of the airway during coughing or dynamic breathing maneuvers and may play an important role in imaging of this disorder in the future.

With 64-detector CT, anatomic coverage up to 4 cm in the z-axis can be obtained during a single acquisition (26). Because of the potential for sampling error with this method, it should be reserved for cases of suspected focal malacia, such as in patients with paratracheal vascular anomalies. This limitation will likely be overcome by the recently introduced volumetric 320-detector CT scanners, which provide up to 16 cm of anatomic coverage in a single rotation. This technology shows much promise for evaluating TBM because it can cover the entire central airways in most pediatric patients. However, because of the relatively higher radiation dose associated with cine imaging compared with volumetric multidetector CT imaging, future work is necessary to determine the optimal dose reduction methods for this technology and its added value in comparison to traditional paired inspiratory-expiratory methods.

Conclusion

Recent advances in multidetector CT, including higher spatial resolution, faster speed, greater anatomic coverage, and higher-quality MPR and 3D reconstruction images, have given rise to much-improved methods in assessing dynamic central airway disease processes such as TBM in infants and children. Familiarity with multidetector CT protocols, postprocessing CT imaging methods, and visual and quantitative analysis of the central airways for TBM will enable radiologists to (a) accurately diagnose TBM in infants and children, (b) determine its degree and extent, (c) assess for predisposing conditions, (d) aid in preoperative or preprocedure planning, and (e) quantify response of treatment to intervention. Readers can view a short video demonstration of our technique online (Movie, http://radiology.rsnaejnls.org/cgi/content/full/252/1/7/DC1).

References

Lee EY, Boiselle PM. Multidetector CT of tracheobronchomalacia in infants and children.


