Pediatric Large Airway Imaging: Evolution and Revolution

Mark C. Liszewski, MD[1*]

Pierluigi Ciet, MD, PhD[2,3,4]

Abbey J. Winant, MD[5]

Edward Y. Lee, MD, MPH[5]

[1]

[2] **Department of Radiology and Nuclear Medicine, Erasmus MC -Sophia Children's Hospital, Rotterdam, The Netherlands**

[3] **Department of Pediatric Respiratory Medicine, Erasmus MC -Sophia Children's Hospital, Rotterdam, The Netherlands**

[4] **Department of Radiology, University Hospital of Cagliari, Cagliari, Italy**

[5] Department of Radiology, Boston Children's Hospital and Harvard Medical School, 300 Longwood Avenue, Boston, MA 02115

*Corresponding author

ABSTRACT

Infants and children often present with nonspecific respiratory symptoms referable to the airway. For these pediatric patients, airway imaging is frequently performed in order to evaluate for underlying disorders of the large airway. Various imaging modalities have been used to evaluate pediatric large airways, and pediatric airway imaging techniques have continued to evolve. Therefore, clear understanding of the current status and new advances in pediatric large airway imaging is essential for practicing radiologists to make timely and accurate diagnoses, which can lead to optimal pediatric patient management.

KEY WORDS

Large airway; Imaging evaluation; Imaging advances; pediatric; infants; children

INTRODUCTION

Nonspecific respiratory symptoms are a common indication for medical imaging of the neck and chest in children (*1*). Large airway disorders are a frequent and important cause of pediatric respiratory symptoms, and high quality airway imaging is essential for prompt and accurate diagnosis. Various imaging modalities, including radiography, fluoroscopy, Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), have been used to evaluate the large airways in children, and the roles of these complementary modalities have continued to evolve. Clear understanding of the current status and new advances in pediatric large airway imaging is essential for practicing radiologists.

Therefore, this article first reviews the clinical utility and complementary roles that radiography, fluoroscopy, CT, and MRI play in the evaluation of pediatric large airway disorders in current clinical practice, highlighting practical applications as well as novel innovations that are essential to the noninvasive diagnosis of various pediatric large airway disorders. In addition, commonly encountered congenital and acquired disorders of pediatric large airways are reviewed, including conditions causing static and dynamic abnormalities of the large airway.

CURRENTLY AVAILABLE IMAGING MODALITIES AND TECHNIQUES

Four main imaging modalities that have been used for evaluation of pediatric large airway disorders are: radiography, fluoroscopy, CT and MRI. Among them, CT and MRI have undergone major imaging advances during the past two decades. The clinical utilities of

currently available imaging modalities for evaluating pediatric large airway disorders are briefly discussed in the following section.

Radiography

Due to widespread availability and low cost, frontal and lateral radiographs of the neck and chest are the usual first-line imaging studies for evaluation of the large airways in the pediatric population. High-detail radiography of the large airways may be achieved using a magnified high kilovoltage (kV) technique, in which the anteroposterior (AP) view is tightly coned to the neck and selectively filtered to eliminate overlap from the cervical spine. In addition, the lateral view is performed at end-inspiration with the neck in an extended position to optimize visualization of the large airways. Standard frontal and lateral views of the chest may also be helpful for evaluation of the lower large airways, and expiratory or lateral decubitus views may be used when evaluating for the secondary signs of airway pathology, such as air trapping.

Fluoroscopy

Airway fluoroscopy may be used to detect changes in large airway caliber throughout the respiratory cycle in real time, in order to diagnose conditions that lead to dynamic abnormalities of the large airways, such as tracheomalacia and bronchomalacia. Similar to radiography, the main benefit of fluoroscopy is its wide availability and relative low cost. Consequently, fluoroscopy has been used as a first-line imaging test for tracheomalacia and bronchomalacia. However, airway fluoroscopy has relatively lower sensitivity for detecting laryngotracheal pathology in children (*2, 3*), and advances in cross sectional imaging with CT

and MRI have allowed for these modalities to be used with increased frequency to evaluate dynamic condition of the large airways in children (*3-8*), as discussed in the following sections.

Computed Tomography

Currently, multidetector computed tomography (MDCT) is the preferred non-invasive imaging test for the evaluation of the large airways in the pediatric population (*5, 6*). Static abnormalities of the large airway are typically assessed with imaging performed at end-inspiration, whereas dynamic pathologies of the large airway can be assessed with paired end-inspiratory and end-expiratory imaging, cine MDCT during free breathing, or four-dimensional (4D) MDCT during free breathing (*4, 9, 10*). Modern MDCT scanners, particularly those with higher row detectors, can achieve rapid scan times that produce images with minimal motion artifact, allowing for imaging of infants and young children without sedation. Assessing for dynamic large airway disorders with paired inspiratory and expiratory MDCT requires intubation in infants and younger children that are unable to follow breathing instructions; however, paired inspiratory and expiratory MDCT can usually be obtained without sedation in older children (*10, 11*). Newer cine MDCT and 4D-MDCT techniques can dynamically assess the pediatric large airways during free breathing and can be performed without sedation, even in infants and younger children (*6, 12, 13*). Although the large airway is often well assessed without intravenous contrast (due to intrinsic contrast between air-filled airway and adjacent soft tissues), the addition of intravenous contrast is often utilized in order to evaluate the adjacent mediastinal structures and assess for vascular anomalies that may be associated with large airway narrowing (*10, 14*).

Although CT has the advantage of producing high-detail cross-sectional images of the large airway and adjacent thoracic structures, often without the need for sedation, the major disadvantage of CT is exposure to ionizing radiation in this vulnerable patient population. In addition, multiphase dynamic MDCT imaging does increase the ionizing radiation dose. In order to reduce radiation dose, careful consideration of the technical CT parameters, such as utilizing reducing the milliamperage (mA) on expiratory CT images, is typically recommended (*15*). Careful clinical consideration of the risks and benefits of imaging with modalities that use ionizing radiation is important, and alternative imaging modalities should be considered, although they may decrease diagnostic yield.

Magnetic Resonance Imaging

MRI has been widely adopted as a preferred imaging modality in the pediatric population due to its superior contrast resolution and lack of ionizing radiation. However, imaging of the large airway with MRI presents challenges due to limited signal from aerated lung, motion artifact, and signal dephasing at air-tissue interfaces[]. Advances in MR scanner technology, such as the development of less motion-sensitive sequences utilizing radial and helicoidal k-space acquisitions (to decrease motion artifact), has improved large airway imaging quality, allowing MRI of the large airway to be possible (*7*). MRI is now used for evaluation of the large airway in children in many pediatric institutions with specialized expertise and is beginning to be adopted widely.

In young children who are unable to follow breathing instructions, anesthesia is generally required for MR imaging of the large airways, and the risks of anesthesia must be

weighed against the benefits of avoiding ionizing radiation (*16*). Older pediatric patients that can follow breathing instructions can often complete the MRI without anesthesia, and preparation with coaching and simulation prior to the exam greatly improves the likelihood of success (*16, 17*).

MRI airway protocols can be divided into static protocols, optimized for the evaluation of fixed abnormalities of the large airways, and dynamic protocols, which are optimized for the evaluation of large airway abnormalities that change during the respiratory cycle. Suggested MRI static and dynamic airway imaging protocols are presented in Tables 1 - 3. Contrast-enhanced MR sequences may be helpful depending on the indication, and contrast or non-contrast MR angiography (MRA) should be performed when evaluating for the presence of a vascular ring (*18*).

EVOLUTION AND REVOLUTION: PEDIATRIC LARGE AIRWAY IMAGING

Imaging of the pediatric large airway has undergone substantial advances in recent decades. In the past, radiography and fluoroscopy were the only imaging modalities available to evaluate the pediatric large airway. Although highly specific, radiography and fluoroscopy have low sensitivity for the detection of the majority of pediatric large airway disorders (*19, 20*), and diagnosis often relied heavily on invasive tests, including bronchoscopy.

The development of CT revolutionized diagnostic imaging evaluation of the pediatric airway, providing a noninvasive imaging modality that is both highly sensitive and specific for

pediatric large airway disorders (*5, 10*). With development of MDCT scanners with higher numbers of detectors and faster gantry rotation times, modern CT scanners can essentially "freeze motion", allowing for pediatric large airway imaging without anesthesia in most cases. Novel cine CT and 4D dynamic multiphase CT now provide sensitive and specific diagnostic imaging tools that can detect dynamic large airway disease, without an invasive test (e.g., bronchoscopy) (*13, 14, 21*). The major advantages of CT must be weighed against the risk of ionizing radiation, which is potentially more harmful in children.

MRI provides the benefit of a cross-sectional imaging modality with excellent contrast resolution that, unlike CT, does not require ionizing radiation. This main benefit has led to the latest evolution of pediatric airway imaging: the development of MRI for the static and dynamic evaluation of the pediatric large airway (*7, 22, 23*). The development of ultrafast MR imaging sequences has begun to address motion artifact, the main impediment to high quality diagnostic MR evaluation of the pediatric large airways (*7, 22, 23*). Ultrafast MR sequences reduce the need for anesthesia and have led to the development of cine MRI, providing a radiation-free alternative to evaluate the pediatric airway (*7, 22, 23*). Currently only available in centers with specific expertise, MRI is likely be more widely utilized for evaluation of the pediatric large airway as ultrafast MR imaging techniques becomes more widely available.

SPECTRUM OF PEDIATRIC LARGE AIRWAY DISORDERS

Static Imaging Evaluation

Congenital Large Airway Malformations

Congenital malformations that result in fixed anomalies of the large airways can be assessed with static imaging protocols. The most commonly encountered fixed congenital malformations include: tracheobronchial branching anomalies, congenital tracheobronchial stenosis, bronchial atresia, and airway narrowing due to extrinsic compression (from vascular ring or pulmonary sling) (*7, 8*).

Tracheobronchial Branching Anomalies

Examples of tracheobronchial branching anomalies include tracheal bronchus, bridging bronchus, esophageal bronchus and cardiac bronchus (*5, 6*). Tracheal bronchus is an anomalous segmental bronchus that arises from the trachea **(Figure 1)**. A tracheal bronchus may be a displaced bronchus, supplying a normal segment of the tracheobronchial tree; a supernumerary bronchus, existing in addition to a normally segmented tracheobronchial tree; or a rudimentary bronchus, with a blind-ending termination (*9, 24, 25*). Tracheal bronchus is most often asymptomatic, but can occasionally cause recurrent atelectasis, pneumonia, and hemoptysis (*8*). Bridging bronchus is an anomalous bronchus that crosses the midline, is associated with pulmonary sling, and is frequently narrowed due to congenital stenosis, bronchomalacia or extrinsic compression from pulmonary sling (*25, 26*) **(Figure 2)**. Esophageal bronchus is an anomalous bronchus that arises from the esophagus, and typically presents in the neonatal period with severe aspiration due to esophageal contents directly entering the lung **(Figure 3)**. Cardiac bronchus is a supernumerary bronchus that typically originates from the right main bronchus or bronchus intermedius and travels in parallel with the bronchus

intermedius toward the pericardium. Cardiac bronchus may end blindly or terminate in disorganized parenchyma, cystic spaces, or an aerated lobule.

Congenital Tracheobronchial Stenosis

Congenital tracheobronchial stenosis is a rare condition in which the tracheal or bronchial diameter is reduced by greater that 50% (*27*) **(Figure 4)**. Stenosis can be focal or over a long distance and may be associated with cartilaginous rings. Affected pediatric patients are frequently misdiagnosed with asthma, and correct diagnosis is often delayed (*28*). CT is the current imaging test of choice for diagnosing congenital tracheobronchial stenosis, although MRI is being utilized in centers with expertise (*27*) **(Figure 5)**. CT can also provide follow-up evaluation after surgical repair or stent placement **(Figure 6).** On imaging, congenital tracheobronchial stenosis, the large airway narrowing is fixed throughout the respiratory cycle, and can be differentiated from tracheobronchomalacia (TBM) with inspiratory/expiratory imaging or cine imaging (*23*).

Bronchial Atresia

Bronchial atresia is a condition in which a segmental bronchus is focally occluded and the lung distal to the atresia is isolated from the tracheobronchial tree. The interruption of the bronchus causes mucous to collect within the airway distal to the atresia, forming a bronchocele (*25*). The lung distal to the atresia is typically aerated via collateral pathways of aeration (e.g., pores of Kohn and channels of Lambert) resulting in air-trapping and hypoxia-mediated oligemia, resulting in hyperlucent lung surrounding the bronchocele (*7*). Bronchocele and hyperlucent surrounding lung segment may be first detected on radiographs, however,

diagnosis is typically confirmed with CT **(Figure 7A)**. MRI may be used as an alternative to CT in centers with expertise. In particular, the characteristic bronchocele is typically well-visualized on T2-weighted MR sequences as a tubular T2-hyperintense structure, with relative hypointense signal in the surrounding pulmonary segment (*7*) **(Figure 7B and 7C)**.

Vascular Rings and Sling

Fixed large airway narrowing may be due to extrinsic compression, such as congenital vascular rings and pulmonary sling. Examples of vascular rings include double aortic arch, right aortic arch with aberrant left subclavian artery, cervical aortic arch, and left aortic arch with right descending aorta and right ligamentum arteriosum encircle the trachea (*29*) **(Figure 8)**. Pulmonary sling is characterized by the left main pulmonary artery originating from the right pulmonary artery (instead of the main pulmonary artery), with the anomalous left pulmonary artery typically compressing the large airway (*26, 30*) **(Figure 2)**. In addition, intrinsic large airway narrowing and branching anomalies are frequently associated with pulmonary sling (*26, 30*).

Vascular ring and pulmonary sling may be initially suspected on radiography, especially in cases with abnormal aortic arch compressing the airway. Echocardiography in the fetal and neonatal periods is often able to diagnose vascular ring and sling, but may be limited especially in older children, due to poor sonographic windows (*29*). Contrast-enhanced CTA is currently the preferred test for definitive diagnosis of suspected vascular ring or pulmonary sling given its superior ability to visualize the vascular anomaly and associated airway narrowing, often without the need for sedation. In many institutions, contrast enhanced and non-contrast

enhanced MRA is becoming the preferred modality for diagnosis of vascular ring and pulmonary sling due to the lack of ionizing radiation. As previously described, sedation is often required for MRA in young children, and consequently, the risks of anesthesia must be weighed against the benefits of limiting ionizing radiation when considering CTA versus MRA (*7*).

Acquired Large Airway Disorders

Disorders of the large airway may be acquired, for example, secondary to trauma, infection and neoplasm. Depending on the specific condition, most acquired large airway disorders are best diagnosed with static imaging protocols.

Post-traumatic Large Airway Disorders

Post-traumatic disorders of the airway may occur due to iatrogenic injury, blunt trauma, or penetrating trauma. The most common post-traumatic disorders include tracheal stenosis and tracheobronchial laceration. Tracheal stenosis is most often related to intubation or tracheostomy tube, and may occur more frequently in children with a history of multiple endotracheal intubations, prolonged endotracheal intubation, or endotracheal intubation with an inappropriately large tube (*31*) **(Figure 9)**. Acquired tracheal stenosis results in tracheal luminal caliber narrowing, which may be seen on radiography, however is best assessed on CT or MRI. Tracheobronchial laceration may be iatrogenic, most often a complication of bronchoscopy, or non-iatrogenic and post-traumatic (e.g. high energy trauma) (*32*). Tracheobronchial laceration typically presents with dyspnea and stridor and subcutaneous

emphysema, which may be evident as crepitus on physical examination. Typical findings on radiography include pneumomediastinum, subcutaneous emphysema, pneumothorax, and fallen lung sign. CT is often needed to clearly delineate the site of injury (*32*) **(Figure 10)**.

Infectious Large Airway Disorders

Various infectious can affected pediatric large airways. Among them, the most common infectious large airway disorder in the pediatric population is tuberculosis (TB) caused by Mycobacterium tuberculosis (MBT) (5, 35) **(Figure 11)**. Large airway abnormality from TB infection in infants and children is typically due to the enlarged mediastinal lymphadenopathy with associated extrinsic large airway compression and subsequent narrowing. Accurate recognition of typical low attenuation (on CT) and/or calcified mediastinal lymphadenopathy often associated with TB infection can helpful for timely and accurate diagnosis, although a definitive diagnosis of TB is made by identifying MBT in a clinical sample (e.g., sputum, pus, or tissue biopsy). Mediastinal fibrosis, which can be idiopathic or a sequela with histoplasmosis infection, can also result in pediatric large airway abnormalities, however these are much less common than TB-related pediatric large airway abnormalities globally (5, 35).

Neoplastic Large Airway Disorders

Primary large airway neoplasms are relatively rare in the pediatric population. Due to their rarity and often non-specific presenting symptoms, diagnosis is often missed or substantially delayed. Two primary pediatric large airway neoplasms with characteristic imaging findings are hemangioma and carcinoid tumor (5, 35) **(Figure 12)**. Both primary large airway neoplasms are highly vascular tumors with marked contrast enhancement. In addition, the

patient age at onset and location within the large airway can be helpful imaging clues for accurate diagnosis of these primary airway neoplasms. Hemangioma, which is a benign tumor, typically occurs in infants and neonates in the subglottic region. In contrast, carcinoid tumor, which is the most common primary malignant large airway neoplasm in the pediatric population, typically occurs in adolescents in the bronchi. While large airway hemangioma in infants and neonates may spontaneously involute, carcinoid tumor requires surgical resection (5, 35).

Dynamic Imaging Evaluation

Tracheobronchomalacia (TBM) is a condition in which the integrity of the trachea or bronchi are compromised due to intrinsic weakness in the airway wall or chronic external compression, chronic inflammation, trauma, or infection, leading to airway collapse when intrathoracic pressure becomes positive during the expiratory phase of the respiratory cycle (*10, 33*). Three types of TBM are described (*34*). Type I (also known as primary tracheobronchomalacia) and is characterized by excessive collapse of the large airway during expiration in the absence an abnormal structure causing extrinsic compression. Type II is characterized by extrinsic compression of the large airway by a vascular anomaly, such as a vascular ring or pulmonary sling, chest wall deformity, or intrathoracic mass. Type III is characterized by acquired large airway damage due to mechanical ventilation, tracheostomy, or an inflammatory condition.

In TBM, the large airway is often normal in caliber during inspiration, when negative intrathoracic pressure helps to hold the airway open. Consequently, TBM is often missed on standard single end-inspiratory phase imaging. Because the abnormality in TBM is dynamic, typically only visible in the expiratory phase, dynamic imaging through both inspiration and expiration is required for diagnosis **(Figure 13)**. Imaging protocols may include two-phase static imaging (e.g. end-inspiration and end-expiration), cine imaging during free breathing, and four-dimensional dynamic CT imaging during free breathing where a three-dimensional rendering of the large airway is imaged through time (*6, 7, 10, 15, 33, 35*). Although bronchoscopy is the gold standard for the diagnosis, dynamic imaging with CT or MRI have been utilized with increased frequency due to the benefits of avoiding invasive bronchoscopy. At this present time, CT protocols for dynamic evaluation of the large airway have been in use for relatively long time and are well-established (*5, 10, 33, 35*). MRI protocols have gained attention due to the benefit of avoiding ionizing radiation, and are being utilized in centers with specialized expertise in place of CT (*7, 22, 36*). Detailed MRI protocol for dynamic large airway evaluation is shown in **Tables 2 and 3**.

FUTURE DIRECTIONS

Diagnostic imaging of the pediatric large airway has undergone a major evolution from radiography to modern cross sectional evaluation of the pediatric large airway during multiple phases of the respiratory cycle with 3D or 4D reformations utilizing CT and MRI. Refinement of

MR imaging techniques to allow imaging without motion artifact and eliminate the need for administering sedation in children is an important area of future development.

CONCLUSION

Airway imaging is frequently performed to evaluate nonspecific respiratory symptoms in children and infants. It is essential that radiologists are familiar with the variety of imaging modalities and techniques, as well as characteristic imaging findings of pediatric airway disorders in order make timely and accurate diagnoses to guide appropriate management.

REFERENCES

1. J. C. Baez, P. Ciet, R. Mulkern, R. T. Seethamraju, E. Y. Lee, Pediatric Chest MR Imaging: Lung and Airways. *Magn Reson Imaging Clin N Am* **23**, 337-349 (2015).
2. A. Isaiah, K. D. Pereira, Laryngotracheal anomalies and airway fluoroscopy in infants. *Int J Pediatr Otorhinolaryngol* **97**, 109-112 (2017).
3. C. Wallis *et al.*, ERS statement on tracheomalacia and bronchomalacia in children. *Eur Respir J* **54**, (2019).
4. M. Ngerncham, E. Y. Lee, D. Zurakowski, D. A. Tracy, R. Jennings, Tracheobronchomalacia in pediatric patients with esophageal atresia: comparison of diagnostic laryngoscopy/bronchoscopy and dynamic airway multidetector computed tomography. *J Pediatr Surg* **50**, 402-407 (2015).
5. E. Y. Lee, S. B. Greenberg, P. M. Boiselle, Multidetector computed tomography of pediatric large airway diseases: state-of-the-art. *Radiol Clin North Am* **49**, 869-893 (2011).
6. E. Y. Lee, E. J. Zucker, R. Restrepo, P. Daltro, P. M. Boiselle, Advanced large airway CT imaging in children: evolution from axial to 4-D assessment. *Pediatr Radiol* **43**, 285-297 (2013).
7. M. C. Liszewski, P. Ciet, E. Y. Lee, MR Imaging of Lungs and Airways in Children:: Past and Present. *Magn Reson Imaging Clin N Am* **27**, 201-225 (2019).
8. M. C. Liszewski, P. Ciet, K. S. Sodhi, E. Y. Lee, Updates on MRI Evaluation of Pediatric Large Airways. *AJR Am J Roentgenol* **208**, 971-981 (2017).
9. S. Yedururi *et al.*, Multimodality imaging of tracheobronchial disorders in children. *Radiographics* **28**, e29 (2008).
10. E. Y. Lee, P. M. Boiselle, Tracheobronchomalacia in infants and children: multidetector CT evaluation. *Radiology* **252**, 7-22 (2009).
11. F. R. Long, R. G. Castile, Technique and clinical applications of full-inflation and end-exhalation controlled-ventilation chest CT in infants and young children. *Pediatr Radiol* **31**, 413-422 (2001).
12. H. W. Goo, Four-Dimensional Thoracic CT in Free-Breathing Children. *Korean J Radiol* **20**, 50-57 (2019).
13. H. W. Goo, Free-breathing cine CT for the diagnosis of tracheomalacia in young children. *Pediatr Radiol* **43**, 922-928 (2013).
14. S. B. Greenberg, U. Dyamenahalli, Dynamic pulmonary computed tomography angiography: a new standard for evaluation of combined airway and vascular abnormalities in infants. *Int J Cardiovasc Imaging* **30**, 407-414 (2014).
15. E. Y. Lee *et al.*, Comparison of standard-dose and reduced-dose expiratory MDCT techniques for assessment of tracheomalacia in children. *Acad Radiol* **17**, 504-510 (2010).
16. J. C. Baez, R. T. Seethamraju, R. Mulkern, P. Ciet, E. Y. Lee, Pediatric Chest MR Imaging: Sedation, Techniques, and Extracardiac Vessels. *Magn Reson Imaging Clin N Am* **23**, 321-335 (2015).
17. E. Salamon, S. Lever, W. Kuo, P. Ciet, H. A. Tiddens, Spirometer guided chest imaging in children: It is worth the effort! *Pediatr Pulmonol* **52**, 48-56 (2017).
18. M. Puderbach *et al.*, MR imaging of the chest: a practical approach at 1.5T. *Eur J Radiol* **64**, 345-355 (2007).
19. M. O. Sanchez, M. C. Greer, I. B. Masters, A. B. Chang, A comparison of fluoroscopic airway screening with flexible bronchoscopy for diagnosing tracheomalacia. *Pediatr Pulmonol* **47**, 63-67 (2012).
20. E. Berg, I. Naseri, S. E. Sobol, The role of airway fluoroscopy in the evaluation of children with stridor. *Arch Otolaryngol Head Neck Surg* **134**, 415-418 (2008).

21. J. Z. Tan, M. Crossett, M. Ditchfield, Dynamic volumetric computed tomographic assessment of the young paediatric airway: Initial experience of rapid, non-invasive, four-dimensional technique. *J Med Imaging Radiat Oncol* **57**, 141-148 (2013).
22. R. A. Faust, K. B. Remley, F. L. Rimell, Real-time, cine magnetic resonance imaging for evaluation of the pediatric airway. *Laryngoscope* **111**, 2187-2190 (2001).
23. P. Ciet *et al.*, Spirometer-controlled cine magnetic resonance imaging used to diagnose tracheobronchomalacia in paediatric patients. *Eur Respir J* **43**, 115-124 (2014).
24. D. R. Biyyam, T. Chapman, M. R. Ferguson, G. Deutsch, M. K. Dighe, Congenital lung abnormalities: embryologic features, prenatal diagnosis, and postnatal radiologic-pathologic correlation. *Radiographics* **30**, 1721-1738 (2010).
25. A. Desir, B. Ghaye, Congenital abnormalities of intrathoracic airways. *Radiol Clin North Am* **47**, 203-225 (2009).
26. W. E. Berdon, O. J. Muensterer, Y. M. Zong, C. L. Backer, The triad of bridging bronchus malformation associated with left pulmonary artery sling and narrowing of the airway: the legacy of Wells and Landing. *Pediatr Radiol* **42**, 215-219 (2012).
27. R. J. Hewitt, C. R. Butler, E. F. Maughan, M. J. Elliott, Congenital tracheobronchial stenosis. *Semin Pediatr Surg* **25**, 144-149 (2016).
28. D. A. Uchida, V. Morgan-Wallace, K. Richards, J. Seidelman, H. R. Muntz, Congenital tracheal stenosis masquerading as asthma in an adolescent: the value of spirometry. *Clin Pediatr (Phila)* **48**, 432-434 (2009).
29. B. D. Kussman, T. Geva, F. X. McGowan, Cardiovascular causes of airway compression. *Paediatr Anaesth* **14**, 60-74 (2004).
30. W. E. Berdon *et al.*, Complete cartilage-ring tracheal stenosis associated with anomalous left pulmonary artery: the ring-sling complex. *Radiology* **152**, 57-64 (1984).
31. G. J. Downing, H. W. Kilbride, Evaluation of airway complications in high-risk preterm infants: application of flexible fiberoptic airway endoscopy. *Pediatrics* **95**, 567-572 (1995).
32. J. B. Moser, K. Stefanidis, I. Vlahos, Imaging Evaluation of Tracheobronchial Injuries. *Radiographics* **40**, 515-528 (2020).
33. E. Y. Lee, D. Litmanovich, P. M. Boiselle, Multidetector CT evaluation of tracheobronchomalacia. *Radiol Clin North Am* **47**, 261-269 (2009).
34. K. A. Carden, P. M. Boiselle, D. A. Waltz, A. Ernst, Tracheomalacia and tracheobronchomalacia in children and adults: an in-depth review. *Chest* **127**, 984-1005 (2005).
35. E. Y. Lee, M. J. Siegel, MDCT of tracheobronchial narrowing in pediatric patients. *J Thorac Imaging* **22**, 300-309 (2007).
36. P. Ciet *et al.*, Cine MRI of Tracheal Dynamics in Healthy Volunteers and Patients With Tracheobronchomalacia. *AJR Am J Roentgenol* **209**, 757-761 (2017).

FIGURE LEGENDS

Figure 1 – Tracheal bronchus in an 10-month-old girl who presented with respiratory distress and recurrent right upper lobe atelectasis. Subsequently obtained bronchoscopy confirmed the diagnosis of tracheal bronchus.

A. Sagittal oblique minimum intensity projection (MinIP) CT image shows an anomalous right upper lobe bronchus (arrow) directly arising from the trachea above the carina.
B. 3D volume-rendered CT image confirms an anomalous right upper lobe bronchus (arrow) also known as tracheal bronchus.

Figure 2 – Bridging bronchus in a 5-month-old girl who presented with shortness of breath and found to have a pulmonary artery sling.

A. Axial minimum intensity projection (MinIP) CT image shows carina (asterisk) and pseudocrina (thin arrow) in addition to bridging bronchus which is an anomalous bronchus that crosses the midline. The caliber of bridging bronchus is small due to underlying congenital stenosis.
B. 3D volume-rendered CT image better demonstrates the entire extent and narrowing of the bridging bronchus.
C. Axial enhanced CT image shows an anomalous left pulmonary artery (arrow) arising from the main pulmonary artery and crossing the midline to the left, consistent with a pulmonary artery sling.

Figure 3 – Esophageal bronchus in a 6-month-old girl who presented with recurrent cough, fever, gagging with feeds, and right lung pneumonia. Frontal fluoroscopy image from upper gastrointestinal study with oral contrast shows a direct communication (arrow) between the esophagus (E) and a right lower lobe bronchus. Distal esophageal stenosis is also seen.

Figure 4 – Congenital tracheal stenosis in a 5-year-old boy who presented with progressively worsening shortness of breath. Subsequently obtained bronchoscopy confirmed the diagnosis of tracheal stenosis.

A. Axial enhanced CT image at the level of upper intrathoracic trachea shows a marked narrowing (arrow).
B. 3D volume-rendered CT image better demonstrates the degree and extent of the congenital tracheal stenosis (arrows). Of note, gaseous distension of the esophagus (asterisk) is also partially visualized.

Figure 5 – Congenital bronchial stenosis in a 2-month-old girl who presented with respiratory distress. Frontal 3D volume-rendered CT image shows a short segment marked narrowing (arrow) involving the distal left main stem bronchus.

Figure 6 – Stent placement of congenital stenosis in the left main stem bronchus in a 9-year-old girl with recurrent bronchial stenosis despite balloon dilatation procedure. Coronal enhanced

CT image shows a metallic stent (arrow) located in the proximal to mid left main stem bronchus. The metallic stent patency can be evaluated with CT.

Figure 7 – Bronchial atresia and congenital lobar hyperinflation, a hybrid congenital lung lesion, in a 16-year-old boy who presented with exercise induced shortness of breath and respiratory distress.

A. Axial lung window CT image shows a bronchocele (arrowhead), bulla (arrow), and hyperinflated portion of lung (asterisk).

B and C. Axial inspiratory T2-weighted MR (B) and expiratory 3D PD-weighted MR (C) images demonstrates increased signal intensity of the bronchocele component (arrowhead) in addition to persistent areas of lung with air trapping and bulla.

Figure 8 – Vascular ring due to right aortic arch with an aberrant left subclavian artery in a 5-year-old girl who presented with respiratory and feeding difficulty.

A. Axial enhanced CT image shows a right sided aortic arch (arrow) with an aberrant left subclavian artery (arrowhead) resulting in tracheal narrowing (T).
B. Bronchoscopy confirmed the tracheal narrowing.

Figure 9 – Acquired tracheal stenosis in a 17-year-old girl who presented with progressively worsening shortness of breath after long term placement of endotracheal tube after motor

vehicle accident. 3D volume-rendered CT image shows a high grade and short segment tracheal stenosis in the subglottic region (arrow).

Figure 10 – Tracheal laceration in a 3-month-old-girl with multiple endotracheal tube placement attempts. Coronal enhanced CT image shows mediastinal air (arrow) adjacent to the left side of trachea with an endotracheal tube placement. Subsequently obtained bronchoscopy showed a tracheal laceration.

Figure 11 – Tuberculosis infection associated large airway narrowing in an 18-month-old girl who presented with fever, cough and weight loss.

A. Frontal chest radiography shows an enlarged mediastinal contour (arrows) suspicious for underlying lymphadenopathy.
B. Coronal enhanced CT image demonstrates multiple mediastinal lymphadenopathy with areas of low attenuation and associated right sided bronchial narrowing.

Figure 12 – Carcinoid tumor in a 7-year-old girl who presented with progressively worsening respiratory distress and right sided chest pain. Axial enhanced CT image shows a markedly enhancing endobronchial tumor (arrow). Surgical pathology confirmed the diagnosis of carcinoid tumor.

Figure 13 – Tracheomalacia in a 4-month-old boy who presented with cough and respiratory distress.

A. Axial enhanced CT image obtained at end-inspiration shows a patent but mild narrowed trachea (arrow). Right upper lobe atelectasis (asterisk) is also seen. E = Esophagus.

B. Axial enhanced CT image obtained at end-expiration demonstrates a complete collapse of trachea (arrow) consistent with tracheomalacia. Right upper lobe atelectasis (asterisk) is also seen. E = Esophagus.

C. Frontal 3D volume-rendered CT image obtained at end-inspiration shows a patent but mildly narrowed trachea (arrow).

D. Frontal 3D volume-rendered CT image obtained at end-expiration demonstrates a completely collapsed trachea (arrow) consistent with tracheomalacia. The longitudinal extent of the tracheomalacia is better visualized on 3D CT reconstructed image than axial CT image. Of note, multifocal right main stem bronchomalacia (arrowheads) are also seen.

TABLES

Table 1: Static MRI Airway Imaging Protocol

Static MRI-protocol for Airways imaging		
Sequence	**Imaging Plane**	**Voxel Resolution (mm^3)**
3D BH PD-T1w RF spoiled gradient recalled echo (GRE) SPGR(LAVA), FLASH (VIBE), T1-FFE (THRIVE)	axial, coronal or sagittal	Min 3.0 x 3.0 x 3.0 Max 1.5 x 1.5 x 1.5
2D BH/FB T1/T2w single shot steady balanced GRE FIESTA, trueFISP, balanced FFE	axial, coronal or sagittal	Min 3.0 x 3.0 x 7.0 Max 1.5 x 1.5 x 4.0
2D FB (Nav/RT/Avg) PD-T2w fat FS spin echo (FSE) (PROPELLER, BLADE, multiVANE XD)	axial	Min 1.0 x 1.0 x 5.0 Max 0.7 x 0.7 x 2.0
3D FB (Nav/RT) PD-T1w ultrashort TE (UTE), zero TE (ZTE)	axial, coronal or sagittal	Min 1.5 x 1.5 x 1.5 Max 0.8 x 0.8 x 0.8
3D FB (Nav/RT) T2w FS FSE (CUBE, SPACE, VISTA)	axial, sagittal	Min 1.5 x 1.5 x 1.5 Max 0.8 x 0.8 x 0.8

BH = breath-hold, FB = free-breathing, RT = pneumobelt respiratory gated
Nav = navigated liver dome, Avg = free-breathing / multiple averaging, FS = fat suppression

Table 2: Dynamic MRI Airway Imaging Protocol

Dynamic MRI airways (multiphase imaging=cine-MRI)		
Sequence	**Imaging Plane**	**Voxel Resolution (mm^3)**
4D (PD-T1w) multifase rf-spoiled 3D GRE (met/zonder ademinstructie) TRICKS-DISCO, TWIST-GRASP, 4D-TRACK	Axial, coronal or sagittal	Min 3.0 x 3.0 x 3.0 Max 2.0 x 2.0 x 2.0
2D multifase (T1/T2w) steady state balanced GRE (met/zonder ademinstructie) FIESTA, trueFISP, balanced FFE	Axial, coronal or sagittal	Min 1.5 x 1.5 x 4.0
4D retrospective FB (PD-T1w) multifase ultrashort TE (4DUTE)	Axial, coronal or sagittal	Min 1.5 x 1.5 x 1.5 Max 0.7 x 0.7 x 0.7
4D retrospective FB (PD-T1w) multifase zero TE (4DZTE)	Axial, coronal or sagittal	Min 1.5 x 1.5 x 1.5 Max 0.8 x 0.8 x 0.8

Table 3: MRI Airway Imaging Sequences

Sequence	SPGR3D BH Volunteer CF (VIPS) BPD (VIBE)	UTE3D BPD (VIBE)	ZTE3D vnav BPD (VIBE)	ZTE4D Volunteer	ZTE3D BH Volunteer	Propeller BPD (VIBE)	2DFD BPD (VIBE)	comments
Acquisition plane	Sagittal	Axial	Axial	Coronal	Coronal	Axial	Coronal	
TR/TE (ms) **flip angle (°)** **RF**	1.5/0.6 2 Selective	5.2/0.032 3 Selective	1.1/0 2 Non-selective	1.4/0 1 Non-selective	1.25/0 2 Non-selective	*/73 90/120 selective	2.3/0.8 5 Selective	*see average in patients
In-plane matrix	120x120	228x228	200x200	150x150	150x150	340x340	128x128	
k-space trajectory **ETL**	Cartesian -	Cones -	Radial -	Radial -	Radial -	Radial blades 14	Cartesian -	
In-plane Field-of-view (FOV) **RecFOV** **No phase wrap** **Actual voxel resolution (mm^3)** **Slices** **Slice thickness**	36 0.75 - 3.0x3.0x3.0 130 3.0	34 - - 1.5x1.5x1.5 230 1.5	30 - - 1.5x1.5x1.5 200 1.5	34 - - 2.2x2.2x2.2 110 2.2	34 - - 2.2x2.2x2.2 110 2.2	34 - 1.4 1.0x1.0x3.5 50-70 3.5	50 - - 3.9x3.9x15.0 7-10 15	
Receiver bandwidth (KHz)	100 90 90	125	62.5	50	62.5	83.33	83.33	
Parallel imaging (ARC)	None 1.5x1.2 1.5x1.2	None	None	None	None	3.0	2.0	
Number of averages **Number of phases** **No. of spokes per segment**	1 1 -	1 1 *	2.5 1 900	7 16 64	1 1 200	2.0 1 14	1 200 / 186 ms per phase -	* depending on respiratory rate
Physiological triggering	BH	Prospective pneumobelt	Prospective projection navigator	Retrospective pneumobelt	BH	Prospective projection navigator	Free breathing	
Acceptance window	-	-	2.0 mm	-	-	2.0 mm	-	
Scan time (sec) RR=20	13s 8s 5-6s x 2BH	4 min 48s	9 min 50s	3 min 10s	20s	5 min 5s*	38s (6-9 min)	*respiratory rate = 26