Magnetic Resonance Imaging of Pediatric Lungs and Airways

New Paradigm for Practical Daily Clinical Use

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Abstract: Disorders of the lungs and airways are among the most common indications for diagnostic imaging in infants and children. Traditionally, chest radiograph has been the first-line imaging test for detecting these disorders and when cross-sectional imaging is necessary, computed tomography (CT) has typically been the next step. However, due to concerns about the potentially harmful effects of ionizing radiation, pediatric imaging in general has begun to shift away from CT toward magnetic resonance imaging (MRI) as a preferred modality. Several unique technical challenges of chest MRI, including motion artifact from respiratory and cardiac motion as well as low signal-to-noise ratios secondary to relatively low proton density in the lung have slowed this shift in thoracic imaging. However, technical advances in MRI in recent years, including developments in non-Cartesian MRI data sampling methods such as radial, spiral, and PROPELLER imaging and the development of ultrashort TE and zero TE sequences that render CT-like high-quality imaging with minimal motion artifact have allowed for a shift to MRI for evaluation of lung and large airways in centers with specialized expertise. This article presents a practical approach for radiologists in current practice to begin to consider MRI for evaluation of the pediatric lung and large airways and begin to implement it in their practices. The current role for MRI in the evaluation of disorders of the pediatric lung and large airways is reviewed, and example cases are presented. Challenges for MRI of the lung and large airways in children are discussed, practical tips for patient preparation including sedation are described, and imaging techniques suitable for current clinical practice are presented.

Key Words: pediatric, magnetic resonance imaging, ultrashort TE, zero TE, 4D cine imaging

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Disorders of the lungs and airways are among the most common indications for diagnostic imaging in infants and children. Traditionally, chest radiograph has been the first-line imaging test for detecting disorders of the pediatric lungs and large airways due to wide availability, low cost, and relative safety. When cross-sectional imaging is necessary, computed tomography (CT) has typically been the next step. However, for the past 2 decades, mainly due to concerns about the potentially harmful effects of ionizing radiation, pediatric imaging has begun to shift away from CT toward magnetic resonance imaging (MRI) as a preferred cross sectional imaging modality in the pediatric population.

Unfortunately, the unique technical challenges of chest MRI, including motion artifact from respiratory and cardiac motion as well as low signal-to-noise ratios secondary to relatively low proton density (PD) in the lung,[1] have slowed this shift from CT to MRI in thoracic imaging. However, technical advances in MRI in recent years, including developments in non-Cartesian MRI data sampling methods such as radial, spiral, and PROPELLER imaging, and the development of ultrashort TE and zero TE sequences that render CT-like high imaging quality with minimal motion artifact have allowed for a shift to MRI for evaluation of the pediatric lung and large airways in centers with specialized expertise.[2] Using these new methods, high-quality diagnostic cross-sectional imaging of the chest can be obtained with MRI without the ionizing radiation required for CT. In addition, because MRI does not require ionizing radiation, imaging can be obtained at multiple timepoints throughout the respiratory cycle without concern for increasing radiation dose. This makes MRI an ideal potential tool for the assessment of dynamic disorders, such as airway collapse during expiration in tracheobronchomalacia (TBM) and air-trapping in cystic fibrosis (CF) and small airways disease.[3–7]

MRI has already begun to be utilized for the evaluation of lung and large airways in centers with specialized expertise, and this article presents a practical approach for radiologists to consider implementing it in their practices. Challenges of MRI for evaluation of the pediatric lung and large airways are discussed, and strategies to mitigate these challenges are described. Considering these challenges, the current role for MRI is reviewed, and example cases are presented. Practical tips for patient preparation including sedation are described and imaging techniques suitable for current clinical practice are presented.

MRI OF PEDIATRIC LUNGS AND AIRWAYS: PAST AND PRESENT

Challenges of MRI for Evaluation of Lungs and Airways

The primary benefit of MRI is the ability to obtain cross sectional images of the thorax without utilizing ionizing radiation, but there are several inherent challenges to

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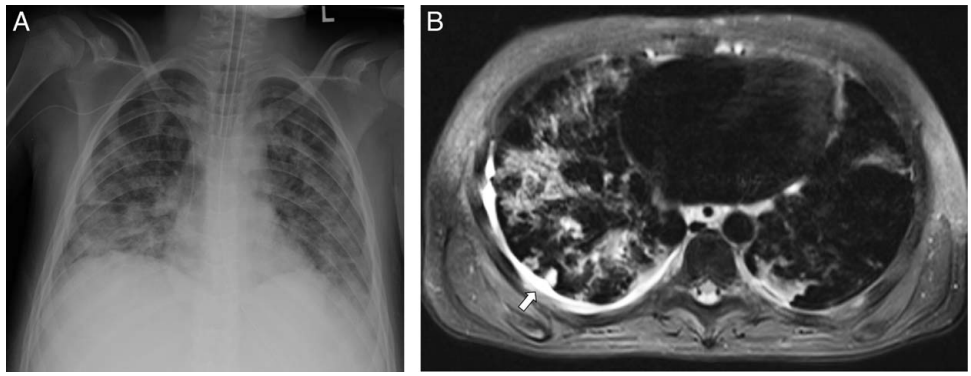

FIGURE 1. A 13-year-old boy with fever and leukocytosis and bronchopneumonia due to *Streptococcus pneumoniae*. A, Frontal chest radiograph demonstrates bilateral multifocal pulmonary opacities. B, Axial nonenhanced T2-weighted fat suppressed MR image shows bilateral patchy regions of T2 hyperintensity throughout bilateral lungs and a small right pleural effusion (arrow).

obtaining high-quality diagnostic MRI of the lungs and airways in children.[8] Because MRI relies on the excitation of protons to produce images, tissues with low PD produce less signal on MRI. The lung and airways are composed of relatively thin tissues with large amounts of intervening air, resulting in a relatively low number of protons in these organ systems.

In addition, children are smaller than adults and the total number of protons in any body part is less, further contributing to the lower signal when imaging the lungs and large airways in children. To overcome the challenges of low PD in smaller pediatric patients, utilization of magnets with higher field strengths, such 3 T MR scanners, has been favored in pediatric imaging of other organ systems. However, imaging at higher field strengths increases artifacts from cardiac and respiratory motion and signal dephasing at air-tissue interfaces, exaggerating the inherent challenges of chest MRI.[8]

Practical strategies to overcome the technical challenges of chest MRI in children have targeted 2 factors. The first factor is to reduce patient motion as much as possible through patient-based techniques. Coaching children before MRI and familiarizing them with the scanner environment using tools like mock MRI scanners are often successful strategies to reduce anxiety and improve motion artifact.[1,9] Children under the age of 6 years are typically unable to hold still and follow breathing instructions for the length of time required for MRI, and therefore usually require anesthesia to complete the exam. Radiologists, radiology technologists, and anesthesiologists must work together to generate MRI free of motion artifact by utilizing apnea at appropriate times throughout the scan. The second factor used to reduce motion artifact is through scanner-based techniques. Utilization of optimized scanning techniques that are less sensitive to respiratory and cardiac movement is a key to successful MRI of the pediatric lung and large airway. This may include the utilization of gradient echo sequences with ultrashort TE to increase the signal-to-noise ratios and improve spatial and temporal while reducing motion artifact.

Current Roles of MRI for Pediatric Lung and Airway Evaluation

Chest radiographs are the first-line imaging test for nearly all disorders of the pediatric lung and large airways. When more detailed cross sectional imaging evaluation is required, CT is generally the most often performed next imaging test. However, as technical advances in MRI have allowed higher quality imaging of the thorax, MRI is being used in place of CT for several clinical indications in centers with expertise in pediatric thoracic MRI.

MRI Evaluation of Pulmonary Infection

Pneumonia is often diagnosed based on clinical features and chest radiographic findings, and most cases do

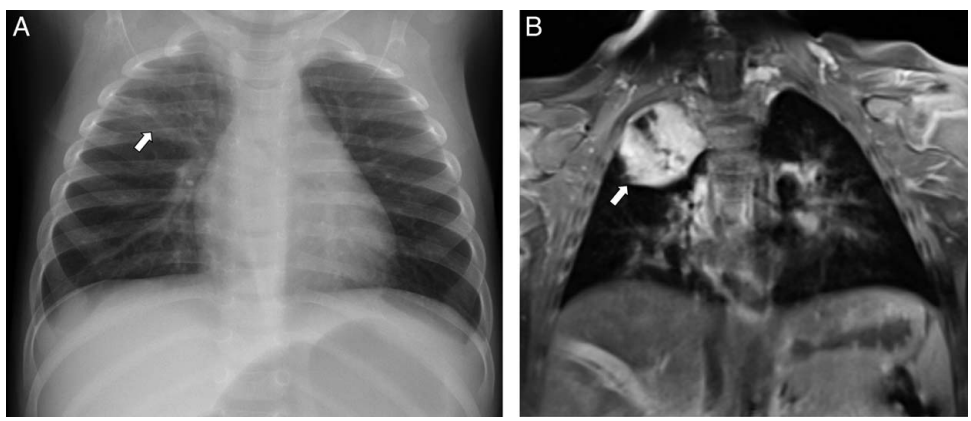

FIGURE 2. A 9-month-old girl with right upper lobe pneumonia. A, Frontal chest radiograph demonstrates right upper lobe hazy opacity (arrow). B, Coronal T2-weighted fat suppressed MR image shows right upper lobe hyperintense consolidation (arrow).

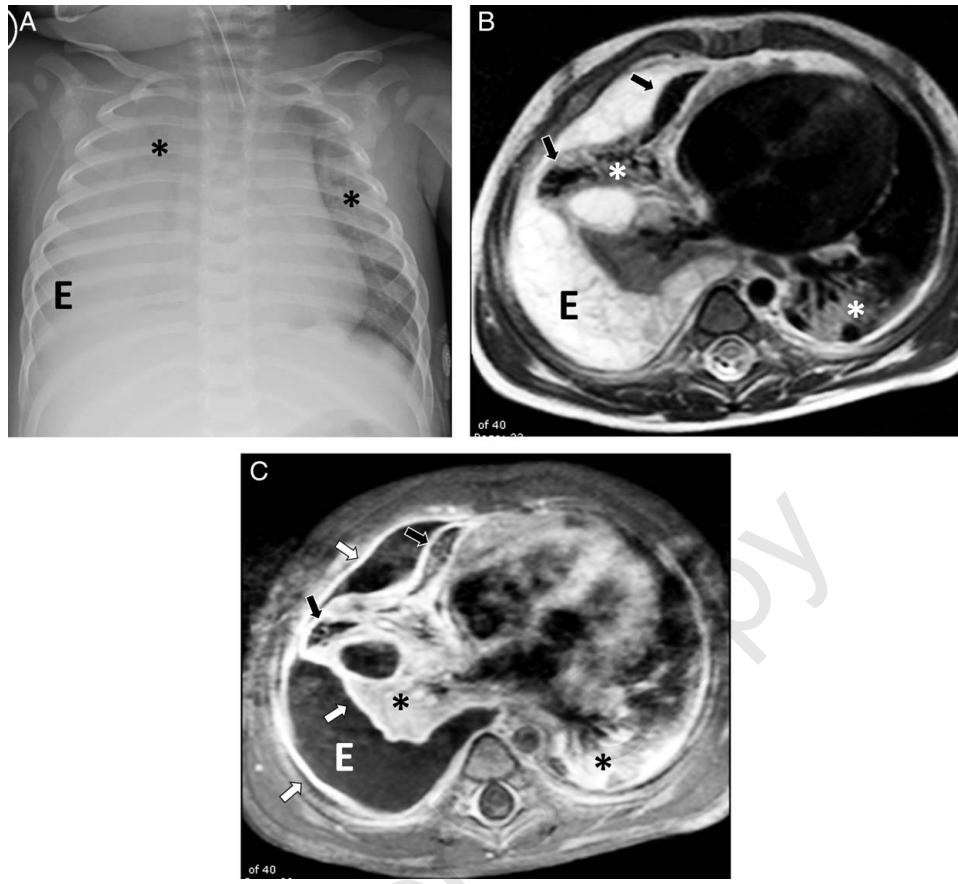

FIGURE 3. A 8-month-old boy with necrotizing pneumonia and empyema. A, Frontal chest radiograph demonstrates bilateral pulmonary opacities (asterisks) and large right pleural effusion (E). B, Axial nonenhanced T2-weighted MRI shows hyperintense signal within bilateral lungs (asterisks) surrounding regions of low signal intensity (black arrows) within the right middle lobe corresponding to regions of necrosis and large right pleural effusion (E) containing septations compatible with empyema. C, Axial enhanced T1-weighted fat suppressed MR image shows hyperenhancement within bilateral lungs (asterisks) surrounding regions of nonenhancement (black arrows) within the right middle lobe corresponding to regions of necrosis and large right pleural effusion (E) with thickening and enhancement of pleura (white arrows) compatible with empyema.

not require cross sectional imaging.[10] Cross sectional imaging may be indicated to assess for complications of pneumonia, such as pulmonary necrosis, empyema, and abscess (Figs. 1–4).[10] Although CT currently remains the most frequently used imaging modality to evaluate complications of pneumonia, multiple studies have shown that MRI is highly accurate in the diagnosis of pneumonia and its complications. Using CT as a reference standard, Gorkem et al[11] found pulmonary consolidation on MRI in 10/10 children with consolidation seen on CT and Sodhi et al[12] found consolidation in 26/26 children with consolidation seen on CT. Studies in adults have shown similar results. For example, in studies comparing MRI with CT as the reference standard, Serra and colleagues reported detection of pulmonary consolidation on MRI in 8/8 adult patients, Attenberger and colleagues in 20/24 lobes, Reiger

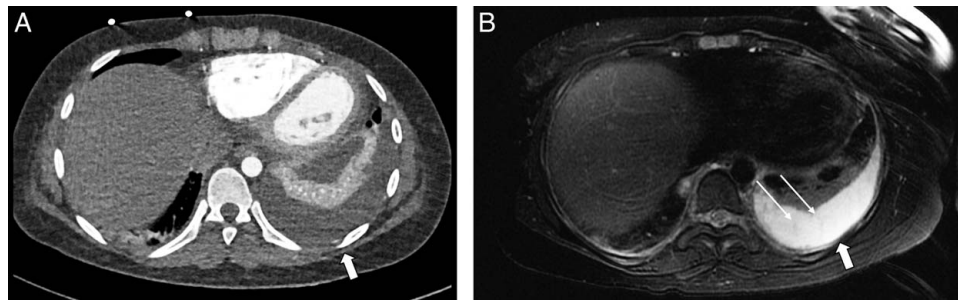

FIGURE 4. A 17-year-old girl with empyema due to retropharyngeal abscess complicated by pneumonia with septic emboli. A, Axial enhanced soft tissue window setting CT image shows left pleural effusion (arrow). B, Axial nonenhanced T2-weighted fat suppressed MRI shows left pleural effusion (wide arrow) containing thin septations (thin arrows) not visible on CT.

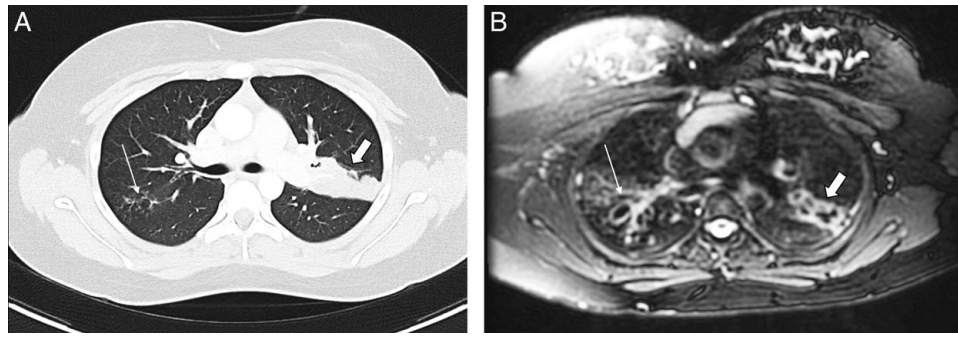

FIGURE 5. A 10-year-old with cystic fibrosis and progression of disease detected on follow-up MRI 2 years later. A, Axial enhanced lung window setting CT image shows tree-in-bud nodularity (thin arrow) in the right upper lobe and bronchiectasis with mucoid impaction (thick arrow) in the left upper lobe. B, Axial nonenhanced T2-weighted fat suppressed MRI obtained 2 years later shows worsening right upper lobe bronchiectasis (thin arrow) and persistent left upper lobe bronchiectasis (thick arrow) with reduced mucoid impaction compared with prior CT.

and colleagues in 30/33 patients, and Ekinci and colleagues in 18/19 cases.[13–16]

MRI also performs well for detection of complications of pneumonia, including pulmonary abscess. Pulmonary abscesses or cavities were detected in 1/1 cases by Gorkem and colleagues, 1/1 cases by Serra and colleagues, 11/11 cases by Sodhi and colleagues, and 4/6 cases by Ekinci anad colleagues.[11–13,16] Pleural effusions from pneumonia are also evaluated well with MRI, with Gorkem and colleagues detecting pleural effusion in 3/3 cases, Sodhi and colleagues in 20/20 cases and Ekinci and colleagues in 14/14 cases who also detecting 3 additional pleural effusions on MRI not seen on CT.[11,12,16]

Lung MRI can bring added diagnostic value in some cases of pulmonary infection. Sodhi and colleagues prospectively investigated the diagnostic accuracy of fast MRI for evaluating pulmonary hydatid disease in children by comparing fast MRI findings to CT findings.[17] They showed that MRI is comparable to CT for accurately detecting lung cysts in pediatric patients with pulmonary hydatid disease and also showed that MRI can provide added diagnostic value by showing internal membranes of cysts that CT missed. Contrast resolution of MRI is superior to CT, which allows for the improved detection of this finding by MRI. Because internal membranes are a specific finding in pulmonary hydatid disease, their detection is important and improves diagnostic accuracy.

MRI Evaluation of Cystic Fibrosis

MRI is being increasingly adopted as a tool to mo nitor disease status and progression in patients with CF (Figs. 5, 6).[4,6,18–20] In several European hospitals, MRI is now used as the primary imaging modality for follow-up of CF patients over 5 years of age or imaging is alternated between MRI and CT in order to reduce exposure to ionizing radiation.[21] Because repeated imaging is often needed in patients with CF to monitor for treatment response and disease progression, MRI is an attractive alternative to CT as it does not require repeated doses of ionizing radiation but still provides diagnostic assessment of the underlying structural lung disease. In addition, the utilization of diffusion-weighted MRI and contrast-enhanced MRI can provide a potential benefit over CT, as they have been shown to be highly sensitive for detection of acute pulmonary exacerbations.[6,22] Recent guidelines in Europe recommend chest MRI as a surrogate marker to assess disease severity and response to treatment during short-term follow-up of symptomatic CF patients.[21] MRI is fairly accurate for diagnosis of bronchiectasis, an important feature of CF, although CT is more accurate. When using CT as a reference standard, Gorkem and colleagues found bronchiectasis in 6/7, Serra and colleagues found it in 9/11, Sodhi and colleagues found it in 4/5, and Ekinci and colleagues found it in 3/4.[11–13,16] Recent papers show that chest MRI can be also used for automatic quantification of pulmonary disease

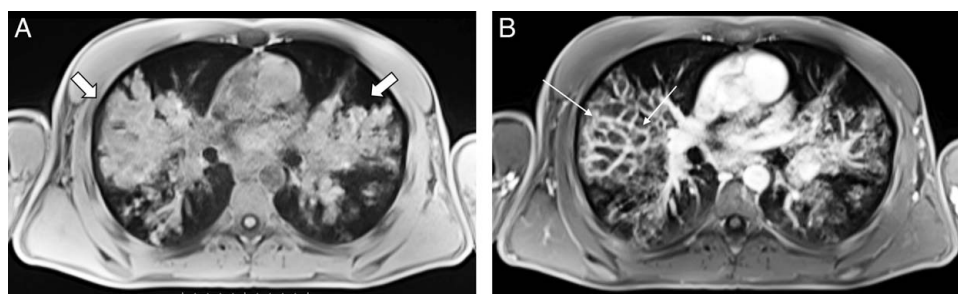

FIGURE 6. A 20-year-old male with cystic fibrosis. A, Axial nonenhanced T1-weighted fat suppressed MR image shows tubular regions of hyperintense signal (wide arrows) corresponding to bronchiectasis and mucous plugging in bilateral upper lobes. B, Axial enhanced T1-weighted fat suppressed MR image shows bronchial wall hyperenhancement and thickening (thin arrows) which are better delineated than on nonenhanced images.

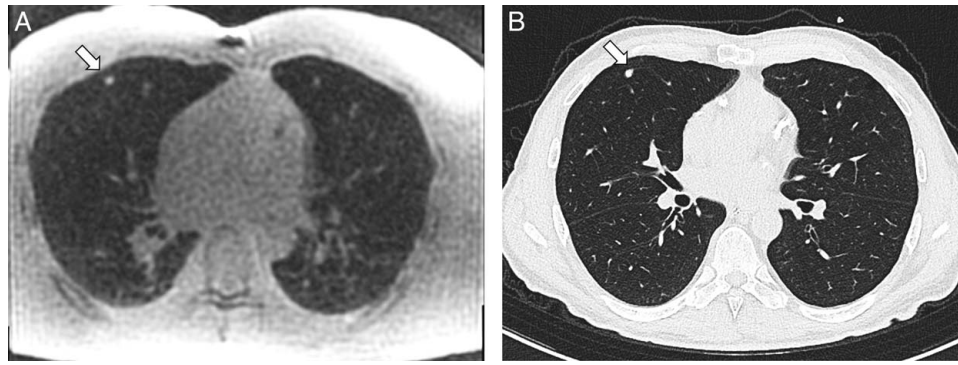

FIGURE 7. A 21-year-old male with incidentally detected pulmonary nodule. A, Axial nonenhanced T1-weighted Zero TE MRI shows a 5 mm pulmonary nodule (arrow) in the right upper lobe. B, Axial nonenhanced lung window setting CT image shows the 5 mm pulmonary nodule (arrow) in the right upper lobe with appearance very similar to MRI.

in patients with CF and can detect progression of early CF lung disease in preschool-aged children.[23,24] Functional techniques such as Fourier decomposition, have been utilized in patients with CF to assess ventilation and perfusion without the need for contrast agents.[25] When implemented into clinical practice, MRI can provide information about ventilation, inflammation, perfusion and structure (VIPS-MRI) in one imaging session.[25]

MRI Evaluation of Pulmonary Nodule

Pulmonary nodules have the potential to be easily visualized on MRI because they are signal-producing structures in a background of air-filled lung, which is intrinsically low in signal (Figs. 7–9). Larger nodules produce a greater amount of signal and are, therefore, more easily visualized on MRI. Several studies have investigated the diagnostic accuracy of MRI compared with CT for detection of pulmonary nodules of various sizes. In an in vitro study by Regier et al,[26] agarose nodules were placed inside porcine lung explants and MRI detected nodules >10 mm with 100% sensitivity, nodules 6 to 10 mm with 83% to 92% sensitivity and nodules <5 mm with 53% to 80% sensitivity. This experiment likely represents a "best case scenario" since motion artifact was not present. In vivo studies evaluating infectious and malignant nodules of various sizes have had detection rates of 5/6 by Gorkem and colleagues, 10/12 by Serra and colleagues, 32/33 by Sodhi and colleagues, and 30/39 by Attenberger and colleagues.[11–13] Although MRI has the potential to detect most pulmonary nodules (larger than 6 mm), CT remains more sensitive for the detection of smaller pulmonary nodules. Because early detection of metastatic disease is essential, and CT outperforms MRI for detection of small pulmonary nodules, CT remains the most appropriate imaging modality for evaluating pulmonary nodules.

MRI Evaluation of Large Airway Disorders

MRI can be an excellent modality for the evaluation of the large airways. Because the large airway is surrounded by mediastinal and hilar tissues with relatively greater PD than the air-filled airway, MRI can produce images of the large airways with excellent contrast resolution.[1,3,5,8,27,28] MRI can be used to assess static disorders of the airway, including tracheobronchial branching anomalies, airway stenosis, and extrinsic compression of the airway (Fig. 10). Because MRI does not utilize ionizing radiation, MRI can be repeated multiple times throughout the respiratory cycle to dynamically assess the large airways without increased radiation dose, as is required for dynamic airway imaging with CT. Therefore, MRI is a very good modality to assess conditions which dynamically affect the airway, namely tracheobonchomalacia (Fig. 11). As new faster sequences are developed, MRI of the airway is an increasingly more practical modality. In a recently published prospective study, Sodhi et al[29] evaluated free-breathing fast T2-weighted multivane XD sequence at 3T MRI for large airway assessment in pediatric patients and showed that this technique is technically feasible and promising for the evaluation of the large airways of pediatric patients in daily clinical practice.

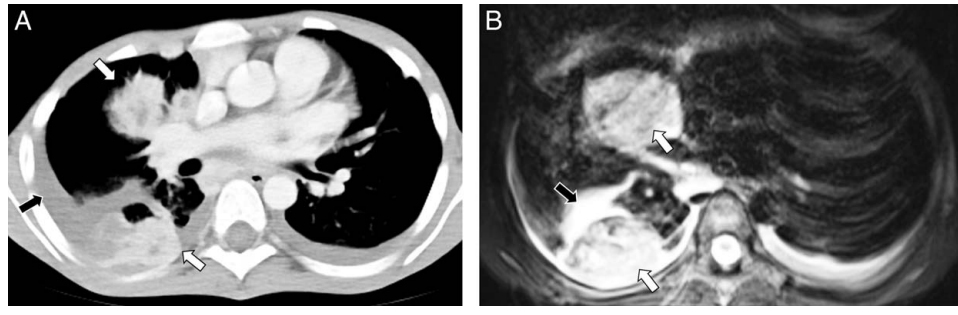

FIGURE 8. A 12-year-old girl with pleural metastases from hepatocellular carcinoma. A, Axial enhanced soft tissue window setting CT image shows pleural masses (white arrows) and right pleural effusion (black arrow). B, Axial nonenhanced T2-weighted fat suppressed MR image shows pleural masses (white arrows) which are more clearly localized to the pleural space than on CT due to outline by hyperintense right pleural effusion (black arrow).

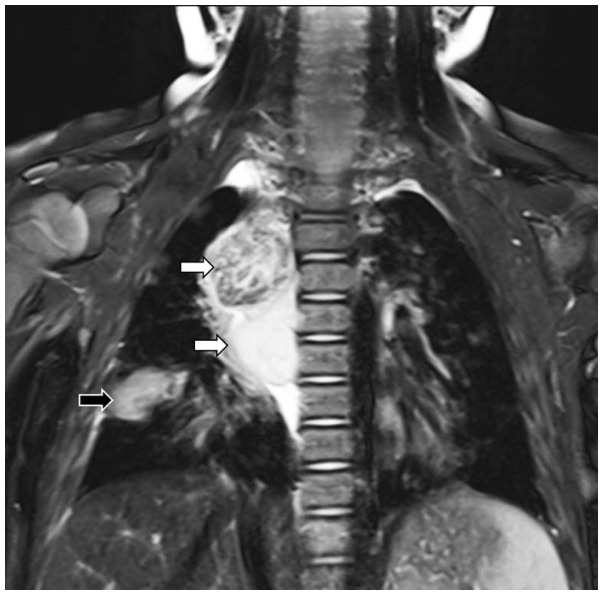

FIGURE 9. A 13-month-old girl with thoracic paraspinal neuroblastoma and pulmonary metastases. Coronal nonenhanced T2-weighted fat suppressed MR image shows paraspinal masses (white arrows) and metastatic mass (black arrow) in the right lower lobe.

PRACTICAL TIPS FOR MRI OF PEDIATRIC LUNGS AND AIRWAYS

Patient Preparation

One of the keys to obtaining high quality diagnostic MRI of the lungs and large airways in children is patient preparation. Because MRI is highly sensitive to motion artifact, prescan measures to reduce patient motion are critical to improving image quality and reducing the need for repeated scanning. Patients must remain very still during the scan, and the loud and unfamiliar environment of the MRI scanner can make this difficult for children to achieve. Use of a mock MRI scanner or a visit to the MRI scanner prior to the time of scan is often helpful for reducing patient anxiety and improving motion artifact on the day of the scan.[30,31]

In addition to holding still, patients often also need to follow breathing instructions depending on the protocol, which may include breath hold, forced expiration, and cough. This may be difficult for many children under 6 years of age to achieve, even if they are calm and able to hold still through the exam. Prescan coaching sessions are highly helpful for improving the success of children who can complete the exams, and also to identify children that may not be able to complete the exam successfully. When children are unable to follow the necessary instructions and perform the required maneuvers, imaging with sedation is necessary.

Sedation

Infants and young children, typically younger than 5 years old, who are unable to hold still and follow breathing instructions for MRI require sedation or anesthesia. In some cases, children may be able to successfully undergo CT without sedation, but would need sedation for the longer scan time required for MRI. In these cases, the risks and benefits of MRI with sedation and CT without sedation must be weighed. The level of sedation and types of medications utilized depend on the imaging protocol and must be carefully administered by a dedicated and experienced team.[32] General anesthesia and intubation may be required for a protocol to assess dynamic collapse of the airway, whereas sedation without intubation may be sufficient for protocols to evaluate the lung parenchyma, depending on the sequences utilized and their susceptibility to motion artifact. Close coordination with the anesthesia team is essential to select the appropriate level of sedation for a given exam, and for coordinating breath-holding and other maneuvers during the scan to achieve high-quality diagnostic imaging. Inspiratory breath-hold scan under anesthesia can be achieved by setting the positive end-expiratory pressure ventilation to maximum. Conversely, expiratory breath-hold images can be obtained by administering an intravenous bolus of anesthetic (usually Propofol) which produces a short-lasting respiratory depression with an end-expiratory apnea of 10 to 15 seconds.[33]

PRACTICAL IMAGING TECHNIQUES: WHAT IS NOW AVAILABLE?

Pediatric Lung Evaluation

Practical MRI protocols to evaluate disorders of the lungs generally include T1 and T2-weighted imaging in axial and coronal planes and may include postcontrast T1-weighted fat suppressed imaging depending on the clinical indication (Tables 1, 2). Imaging sequences that are resistant to motion artifact are needed given significant cardiac and respiratory motion in the thorax. A suggested protocol to evaluate conditions of the pediatric lung includes T2-weighted half-Fourier acquisition single-shot fast spin echo with breath holding, T2-weighted fast spin echo with rotating phase encoding with breath holding, steady state gradient recalled echo with free precession with free breathing, and T1-weighted 3-dimensional (3D) gradient recalled echo with volume interpolation with breath holding.[10] Contrast enhanced T1-weighted 3D gradient echo sequence with fat saturation may be helpful to evaluate the thoracic vasculature or detect enhancement within a neoplastic, inflammatory or infectious process.[10] Contrast enhanced images also enhance detection of bronchial pathology. The addition of diffusion-weighted imaging may also be helpful when evaluating for neoplastic, infectious, and inflammatory processes, as these conditions typically cause diffusion restriction that leads to high signal intensity on diffusion-weighted sequences.[4]

Pediatric Airway Evaluation

Similar to MRI of the lung, MRI of the airway requires sequences that are resistant to motion artifact given the significant cardiac and respiratory motion in the thorax. Protocols may be tailored to evaluate for fixed abnormalities of the airway, such as fixed stenosis, extrinsic compression, or branching anomalies, with static end-inspiration imaging (Tables 1, 2).[1,28] Given the dynamic nature of airway collapse in TBM, evaluation for TBM requires sequences that evaluate the airway during inspiration and expiration. Dynamic MRI to evaluate for TBM may include paired inspiratory and expiratory static images, cine dynamic axial images obtained through the respiratory cycle, or cine dynamic 3D images obtained through the respiratory cycle

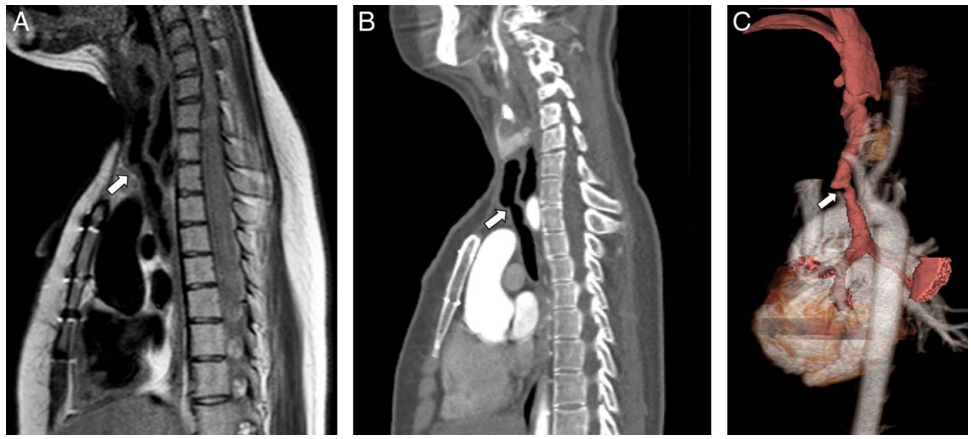

FIGURE 10. A 18-year-old male with tracheal stenosis. A, Sagittal nonenhanced T1-weighted MR image shows tracheal narrowing (arrow). B, Sagittal enhanced soft tissue window setting CT image shows tracheal narrowing (arrow). C, 3D reformatted CT image of the airway and vascular structures shows tracheal narrowing (arrow). full color online

(4D cine imaging) to detect dynamic airway collapse during expiration.[1,28]

Sequences to evaluate fixed disorders of the airway may include 3D PD-T1–weighted radiofrequency spoiled gradient recalled echo with breath hold, 2D T1/T2-weighted single shot steady balanced GRE, 2D PD-T2–weighted fat suppressed fast spin echo, 3D PD-T1–weighted ultrashort TE or zero TE, and 3D T2-weighted fat suppressed fast spin echo. To evaluate the patency of the airway through inspiration and expiration, sequences may include 4D PD-T1–weighted multiphase radiofrequency spoiled 3D gradient recalled echo, 2D multiphase T1/T2–weighted steady state balanced gradient recalled echo, 4D retrospective PD-T1–weighted multiphase ultrashort TE and 4D retrospective PD-T1–weighted multiphase zero TE. 4D imaging produces 3D images of the airway through the respiratory cycle and allows for evaluation of excessive collapse during expiration in TBM. In patients over 5 years of age who can follow breathing instructions breath-hold and dynamic sequences may be obtained. In patients under

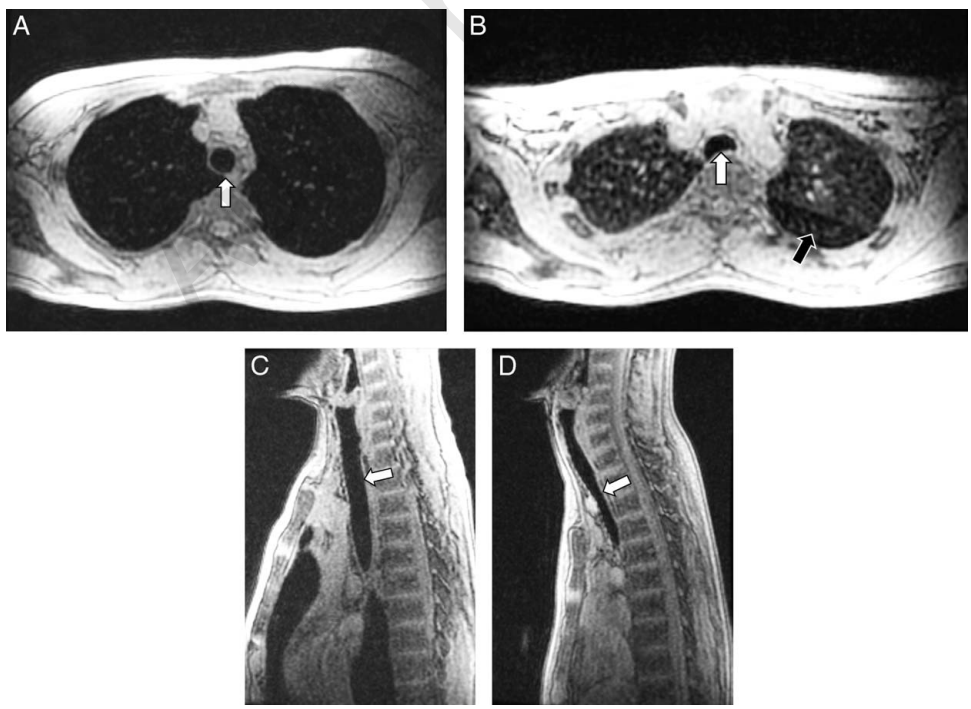

FIGURE 11. A 16-year-old boy with tracheomalacia. A, Axial nonenhanced PD-weighted spirometer-controlled MR image obtained at end-inspiration shows normal caliber trachea (arrow). B, Axial nonenhanced PD-weighted spirometer-controlled MR image obtained at end-expiration shows partial tracheal collapse (white arrow) and air trapping (black arrow) in the superior segment of the left lower lobe. C, Sagittal nonenhanced PD-weighted spirometer-controlled MR image obtained at end-inspiration shows normal caliber trachea (arrow). D, Sagittal nonenhanced PD-weighted spirometer-controlled MR image obtained at end-expiration shows partial tracheal collapse (arrow).

TABLE 1. Lung and Airways MRI Protocol: Morphology

Morphologic MRI-protocol for lung and airways imaging

Sequence	Imaging plane	Breath-hold (BH)/ free-breathing(FB)
3D BH PD-T1w RF spoiled gradient recalled echo (GRE) SPGR(LAVA), FLASH (VIBE), T1-FFE (THRIVE)	Axial, coronal, or sagittal	BH
2D BH/FB T1/T2w single shot steady balanced GRE FIESTA, trueFISP, balanced FFE	Axial, coronal, or sagittal	BH
2D (Nav/RT/Avg) PD-T2w fat FS spin echo (FSE) (PROPELLER, BLADE, multiVANE XD)	Axial, coronal	FB
3D (Nav/RT) PD-T1w ultrashort TE (UTE), zero TE (ZTE)	Axial, coronal, or sagittal	FB
3D (Nav/RT) T2w FS FSE (CUBE, SPACE, VISTA)	Axial, sagittal	FB

Avg indicates free-breathing/multiple averaging; BH, breath-hold; FB, free-breathing; FS, fat suppression; FSE, fast spin-echo; GRE, gradient recalled echo; Nav, navigated liver dome; PD, proton density weighted; RF, radiofrequency; RT, pneumobelt respiratory gated.

5 years age and older patients that are not able to follow breathing instructions but able to hold still for the exam, triggered sequences can be performed to evaluate the airway through the respiratory cycle without breath holding.

CURENT LIMITATIONS OF MRI OF PEDIATRIC LUNGS AND AIRWAYS

Although MRI has shown promise as a potential alternative to CT for a number of conditions affecting the lung and large airway in children, MRI remains limited in some conditions. As described above, MRI is known to be less sensitive for the detection of bronchiectasis, especially in the periphery of the lung.[18] This is due to the lower spatial resolution of MRI compared with CT. For similar reasons, CT is preferred over MRI for the detection of small (sub-6mm) pulmonary nodules, especially in cancer staging. Although MRI may be able to reliably detect larger nodules,[11–13,26] the greater spatial resolution of CT allows for detection of smaller pulmonary nodules. Since early detection of metastatic pulmonary nodules is essential for cancer treatment, CT is preferred over MRI for this indication. MRI may be used as alternative to CT or as complementary problem-solving modality in addition to CT for congenital lung lesion CT for the evaluation of congenital lung lesions and MR angiography can be used as an alternative to CTA for the evaluation of anomalous vessels in bronchopulmonary sequestration.[1,9] However, small anomalous vessels may be better visualized on CTA than MR angiography due to the higher spatial resolution of CT. In general, conditions that require very high spatial resolution for accurate diagnosis are often better evaluated with CT than MRI, and CT should continue to be utilized in these scenarios.

FUTURE DIRECTIONS: WHAT IS PROMISING?

Studies have shown that MRI of the lung and large airways can provide a useful radiation-free alternative to CT

TABLE 2. Lung and Airways MRI Imaging Protocol: Function

Functional MRI-protocol for lung and airways imaging

Sequence	Imaging plane	Breath-hold (BH)/ free-breathing (FB)
Perfusion and MR angiography (MRA)		
Fourier decomposition	Axial, coronal, or sagittal	FB
MR angiography (bright blood imaging, without contrast)→2D and 3D FIESTA	Axial, coronal, or sagittal	FB or BH
MRA with contrast (TRICKS)→ both vessel visualization and perfusion	Axial, coronal, or sagittal	FB or BH
T1 LAVA + gadolinium	Axial, sagittal	FB or BH
Ventilation		
Fourier decomposition	Axial, coronal, or sagittal	FB
Dynamic imaging of airways		
4D (PD-T1w) multifase rf-spoiled 3D GRE TRICKS-DISCO, TWIST-GRASP, 4D-TRACK	Axial, coronal, or sagittal	FB or specific breathing maneuvers (i.e. forced expiration or coughing)
2D multiphase (T1/T2w) steady state balanced GRE FIESTA, trueFISP, balanced FFE	Axial, coronal, or sagittal	FB or specific breathing maneuvers (i.e. forced expiration or coughing)
4D retrospective (PD-T1w) multiphase ultrashort TE (4DUTE)	Axial, coronal, or sagittal	FB
4D retrospective (PD-T1w) multiphase zero TE (4DZTE)	Axial, coronal, or sagittal	FB

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

in children, however, widespread adoption of chest MRI has been slow. The higher cost of MRI, the greater availability of CT, advances in CT technology that allow for fast imaging without sedation, technical advances that have allowed for lower radiation doses with CT, and technical difficulty of obtaining artifact-free MRI images without sedation have resulted in CT remaining the dominant cross-sectional imaging modality for assessment of the lung and large airways in children. Newly developed MRI sequences that are resistant to motion artifact hold great promise. The newest among these are ultrashort TE and zero TE MRI, in which extremely short echo times are utilized to eliminate signal dephasing artifacts at air-tissue interfaces and reduce motion artifact. Many of these sequences are only available for research applications at this time, but as they become more commercially available MRI of the lung and large airways will become a more practical option for many children. As these sequences along with non-Cartesian data sampling techniques (eg, radial, spiral, and propeller) become more widely available and integrated into clinical practice, it is likely that nonsedated pediatric lung and large airway MRI with less motion artifact will be increasingly possible.[2,34]

CONCLUSION

In recent years, pediatric imaging has shifted away from CT and toward MRI for cross-sectional evaluation, largely due to concerns about the potentially harmful effects of ionizing radiation on children. Several technical challenges unique to MRI of the pediatric thorax have resulted in CT remaining the dominant modality for pediatric lung and large airway imaging up to this point. Utilizing appropriate patient selection, patient preparation, and scan optimization, MRI can now be used as an alternative to CT in many situations. With increasing availability of the new generation of MRI scanners and up to date MR sequences and techniques, MRI of the pediatric lung and large airways is becoming an increasingly viable alternative to CT that offers pediatric patients the ability to have high-quality cross-sectional imaging of the thorax without ionizing radiation.

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