Magnetic Resonance Imaging of Pediatric Lung Parenchyma, Airways, Vasculature, Ventilation, and Perfusion State of the Art

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INTRODUCTION

In recent years, magnetic resonance (MR) imaging, a noninvasive imaging modality, has been receiving a lot of attention and is particularly attractive for children, mainly because pediatric patients have greater sensitivity to the potentially harmful effects of ionizing radiation associated

KEYWORDS

- Magnetic resonance imaging
- Pediatric patients
- Lungs
- Airways
- Vasculature
- Ventilation
- Perfusion

KEY POINTS

- Magnetic resonance (MR) imaging has been increasingly used particularly for evaluating pediatric thoracic disorders in recent years.
- Adoption of MR imaging for assessing diseases of the thorax has lagged behind MR imaging in other organ systems because of the technical challenges posed by low proton density within the lungs, magnetic susceptibility differences at lung-air interfaces, and respiratory and cardiac motion.
- New techniques in fast scanning, respiratory triggering, spirometer control, electrocardiography gating, nonenhanced and contrast-enhanced MR angiography, O2-enhanced imaging, and hyperpolarized gas imaging allow MR imaging to be used to evaluate many pediatric thoracic diseases.
- Understanding proper MR techniques and the characteristic MR imaging appearance of various thoracic diseases in pediatric patients is essential to arrive at an early and accurate diagnosis, which in turn, leads to optimal patient care.

INTRODUCTION

In recent years, magnetic resonance (MR) imaging, a noninvasive imaging modality, has been receiving a lot of attention and is particularly attractive for children, mainly because pediatric patients have greater sensitivity to the potentially harmful effects of ionizing radiation associated
with other imaging modalities.\textsuperscript{1,2} However, the physical properties of the lungs and thorax present many challenges to obtaining diagnostic quality MR images, which have limited the clinical use of MR imaging in pediatric patients with various thoracic disorders. Fortunately, many new MR imaging techniques have recently been developed that aim to overcome these challenges. Clear understanding of these new MR imaging techniques and knowledge of their clinical use are paramount. Therefore, the goal of this article is to provide up-to-date information about these techniques, including patient preparation and imaging protocols for the evaluation of lung parenchyma, airways, and thoracic vasculature. Ventilation imaging techniques using hyperpolarized (HP) gas (helium, xenon, and oxygen enhanced) and perfusion imaging techniques using arterial spin labeling (ASL) and contrast-enhanced imaging are also discussed. The potential role for these innovative MR imaging techniques in the evaluation of several pediatric thoracic diseases is highlighted and examples are presented.

**IMAGING TECHNIQUES**

### Patient Preparation

Imaging of children can pose unique challenges to obtaining diagnostic quality MR images, including patient motion and difficulty or inability to follow breathing instructions. These challenges can be magnified when imaging the lungs and airways with MR imaging because complex breathing instructions are often required. Several techniques can be used to minimize these problems, including coaching patients on breathing techniques and the use of sedation and intubation in appropriate situations.\textsuperscript{3} In general, sedation is necessary when imaging infants and uncooperative young children (<6 years old) with MR imaging, but can often be avoided in older children (>6 years old) who are able to perform the necessary respiratory maneuvers with adequate coaching. It is essential that adequate time is devoted to practicing breath-hold techniques with children before MR imaging to reduce patient anxiety and improve diagnostic quality.

### Imaging Protocols

#### Lung parenchymal evaluation

Although computed tomography (CT) remains the reference standard for evaluation of the lung parenchyma, advances in MR imaging have made imaging of infiltrative and solid lung pathologies possible with high sensitivity\textsuperscript{4–9} and interstitial lung disease with fair sensitivity and specificity.\textsuperscript{7} Protocol recommendations have been published\textsuperscript{3,4,10} and a standard 15-minute examination is usually sufficient to answer many clinical scenarios (Table 1).\textsuperscript{4} Additional sequences can be included depending on the specific clinical question to be answered.\textsuperscript{3,4,10}

The basic evaluation of the lung can consist of 5 non–contrast-enhanced sequences, including 3-plane gradient recalled echo (GRE) locator for planning, coronal T2-weighted half Fourier acquisition single-shot turbo spin echo (HASTE) for evaluation of pulmonary consolidation, single breath-hold axial T1-weighted three-dimensional (3D)-GRE (VIBE) for evaluation of smaller parenchymal lesions, free-breathing coronal steady-state free precession (TrueFISP) for basic evaluation of pulmonary and cardiac motion and exclusion of large central pulmonary embolism (PE), and multiple breath-hold axial T2 weighted-short tau inversion recovery (STIR) (T2-TIRM) to evaluate for lymphadenopathy and osseous lesions.\textsuperscript{4} An additional contrast-enhanced 3D-GRE (VIBE) sequence is also useful in some situations, including evaluation of malignancy, infection, and inflammatory disease.\textsuperscript{4} In patients who are unable to cooperate with breathing instructions, free-breathing Propeller (BLADE + navigator) sequences\textsuperscript{11} can be used.

<table>
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<th>Table 1</th>
<th>Basic MR imaging protocol for evaluation of lung parenchyma</th>
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<tr>
<td>Sequence</td>
<td>Imaging Plane</td>
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<tr>
<td>Gradient recalled echo (GRE) locator</td>
<td>3-plane</td>
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<td>Single-shot half Fourier turbo spin echo (HASTE)</td>
<td>Coronal</td>
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<td>3-D GRE volumetric interpolated breath-hold (VIBE)</td>
<td>Axial</td>
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<td>Steady-state free precession (TrueFISP)</td>
<td>Coronal</td>
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<tr>
<td>Short tau inversion recovery (STIR)</td>
<td>Axial</td>
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<tr>
<td>Optional</td>
<td>Postcontrast 3D-GRE VIBE with fat saturation</td>
</tr>
<tr>
<td>Propeller (BLADE + navigator) free breathing\textsuperscript{b}</td>
<td>Axial</td>
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</table>

\textsuperscript{a} Combination of proton density and T1 and T2 contrast.  
\textsuperscript{b} Can be used in place of STIR in patients who cannot perform breath-hold.
instead of breath-hold axial T2-weighted-STIR (T2-TIRM) sequences.

This basic protocol can be expanded to include additional sequences tailored to the specific clinical questions\(^3,4,10\) and several of these specialized sequences are described in the following sections. These protocols have been proposed mainly for use in adults, but they are equally well suited to the pediatric patient population after appropriate patient preparation.\(^5\)

**Large airway evaluation**

Although CT has been the mainstay of airway evaluation,\(^12–16\) recent advances have allowed for the evaluation of large airways using MR imaging.\(^3,12,15,17–19\) Using the basic MR sequences described earlier, it is now possible to image most static diseases of the large airways including bronchiectasis, bronchial wall thickening, mucous plugging, large airway neoplasms, and large airway branching anomalies.\(^6\) Until recently, dynamic imaging of the large airways to evaluate for tracheobronchomalacia (TBM) was only feasible using CT. However, new techniques in spirometer-controlled MR imaging now provide promising imaging alternatives to CT.\(^20\)

Using a spirometer compatible with MR imaging (Fig. 1) and a team comprising a lung function technician, MR imaging technologist, and a radiologist, spirometer-controlled MR imaging can be performed to evaluate for dynamic airway collapse seen in TBM. Approximately 30 minutes before imaging, the patient meets with a lung function technician and practices breathing maneuvers using a spirometer compatible with MR imaging (custom made Masterscope, CareFusion, Houten, The Netherlands). Patients are trained to perform maximum breath-hold times of 15 seconds at at least 95% inspiratory vital capacity (IVC) and 90% expiratory vital capacity (EVC). They are also trained to perform full forced expiration and cough maneuvers starting at IVC. After training, patients are moved to the MR imaging scanner where the lung function technician and MR imaging technologist monitor and communicate with the patient throughout the examination.

The standard protocol to evaluate for dynamic airway changes of TBM begins with a 3-plane GRE localizer sequence performed at IVC. Next, 3D radiofrequency-spoiled gradient echo (SPGR) sequences are performed at IVC and EVC covering the complete thorax to evaluate lung anatomy and measure central airway dimensions. The field of view (FOV) is then narrowed to include only the trachea and main stem bronchi and 3D SPGR sequences are obtained at IVC and EVC. Finally, four-dimensional (4D) temporally resolved imaging of contrast kinetics (TRICKS) acquisitions of the same limited FOV are obtained during forced expiration and cough to image real-time movements of the trachea and main stem bronchi. The scan time to perform these maneuvers is approximately 12 minutes (range 7–15 minutes). Spirometer-controlled MR imaging is only feasible in older children who are able to follow breathing instructions. Dynamic MR evaluation of the airway is a promising new tool that can help to minimize the number of CT scans in pediatric patients suspected of having TBM for an initial diagnosis and follow-up assessment after treatment.

**Thoracic vasculature evaluation**

Typical indications for imaging of the thoracic vasculature in children include evaluation of
vascular anomalies, investigation of lesions with associated abnormal vascular supply, and the study of PE. Imaging protocols include basic T1-weighted and T2-weighted sequences described in detail earlier along with electrocardiography (ECG)-gated black blood single-shot fast spin echo (SSFSE) with double inversion recovery, bright blood 2D or 3D balanced steady-state free precession (SSFP) sequences, and MR angiography. MR angiography sequences can be used with or without contrast. Noncontrast MR angiography sequences rely on SSFP-GRE, double inversion recovery, or time of flight techniques and have been used in the evaluation of the thoracic vasculature and PE. These noncontrast techniques can be repeated numerous times without concern about contrast dose. However, many consider contrast-enhanced MR angiography (CEMRA) to be the preferred method for pulmonary MR angiography given its high spatial and contrast resolution. CEMRA requires breath-hold times of approximately 15 seconds, and is therefore not possible in young pediatric patients who cannot follow breathing instructions. The basic principle behind CEMRA is the acquisition of a heavily T1-weighted sequence after intravenous administration of a paramagnetic contrast agent. Short relaxation times (TR) of less than 5 milliseconds and high flip angles decrease background signal and susceptibility artifacts. 3D techniques can be used to allow for multiplanar reformation. To achieve high contrast between vascular branches and surrounding structures, it is essential to administer the contrast bolus using an automatic power injector with flow rates between 2 and 5 mL/s followed by a saline flush (Table 2). Because patients in need of thoracic vasculature imaging often have varied flow dynamics, optimum timing should be individually adjusted using a test bolus. If the timing is incorrectly calculated and images are obtained in a later phase, enhancement of the pulmonary veins can impair the assessment of the arteries. In cases of arterial/venous superimposition, several postprocessing strategies can be used to differentiate arteries from veins, including cine or stack-mode viewing, continuous rotation, multiplanar reformation (MPR), and maximum intensity projection (MIP). One strategy to avoid the issue of superimposition uses high temporal resolution multiphase acquisitions, which begin at the time of contrast administration and continue through the venous phase, although these sequences have lower spatial resolution.

Ventilation evaluation: HP gas and oxygen-enhanced imaging

HP gas imaging One of the primary technical challenges of lung MR imaging is an inherent low signal-to-noise ratio, because most of the lung is composed of gas-filled spaces where the concentration of water molecules is approximately 1000 times less than that in solid tissue. Given this physical property, there will always be challenges to obtaining signal from lung parenchyma using standard proton MR. Over the past decade, an alternative to proton MR has been developed that obtains signal from inhaled HP 129Xe or 3He, which serve as positive contrast agents as they move through the airways, thus providing a method for imaging ventilation.

To perform HP gas MR imaging, the patient is fitted with an radiofrequency (RF) coil that is tuned to operate at the resonant frequency of 129Xe or 3He, a function that can be performed on most commercial MR scanners. A bag of HP gas is generated in a noble gas polarizer, and the patient inhales the HP gas immediately before imaging (Fig. 2). A static breath-hold, fast, 2D, multislice GRE sequence is then acquired at end inspiration to assess the distribution of ventilated gas (Fig. 3). Excellent image quality can be obtained with both 129Xe or 3He. Gaseous 129Xe has a much higher molecular weight and lower coefficient than 3He, which may result in differences in the flow and distribution of the gases during inhalation. This may make 129Xe more sensitive to airflow abnormalities in obstructive lung diseases (Fig. 4).

Diffusion-weighted imaging (DWI) can also be performed to evaluate the lung microstructure at the alveolar level. Because HP gas molecules move randomly through the airways and alveoli as a result of Brownian motion, the average distance that an HP gas molecule moves in a given period of

| Table 2 Intravenous catheter size, injection rate, and method for MR imaging |
|-----------------|-----------------|-----------------|
| **Intravenous Catheter Size (Gauge)** | **Maximum Injection Rate (mL/s)** | **Injection Method** |
| 24 | 1.0 | Hand injection |
| 22 | 2.0 | Power injection |
| 20 | 2.0–3.0<sup>a</sup> | Power injection |
| 18 | 3.0–4.0<sup>a</sup> | Power injection |

<sup>a</sup> In pediatric patients, diagnostic thoracic MR imaging and MR angiography examinations can usually be performed with injection rates of ~2 mL/s.
time is determined by the alveolar microstructure. Therefore, the random movements of HP gas molecules are influenced by disease processes that cause the alveoli to be abnormally expanded (Fig. 5). Using the same principles used in DWI of the brain and body, apparent diffusion coefficient (ADC) maps can be obtained, providing an assessment of lung microstructure including alveoli and acini, with larger airspaces leading to higher ADC values (Fig. 6).\textsuperscript{41} DWI has been performed with both $^{129}$Xe or $^3$He, and qualitatively similar results have been obtained with both gases (Fig. 7).\textsuperscript{36} An increase in mean $^3$He ADC has been observed with increasing age in children from 4 years old to adulthood, suggesting that HP gas DWI can detect the known age-related increase in alveolar size during childhood (Fig. 8)\textsuperscript{42} Furthermore, increased ADC values have been detected in children with a history of preterm birth and subsequent bronchopulmonary dysplasia compatible with histologic evidence that these children have enlarged alveoli, which are reduced in number (Fig. 9). Thus, HP gas DWI is a noninvasive technique that can be used to evaluate normal alveolar development and the alterations in lung development caused by pediatric lung diseases.

Although most clinical MR scanners have the ability to perform HP gas imaging, it is not in widespread use because $^{129}$Xe and $^3$He are not readily available in most centers. Global supplies of $^3$He are limited and expensive because the market price of $^3$He is partially determined by governmental and political considerations.\textsuperscript{6,43} Therefore,
129Xe has been adopted by many as the imaging agent of choice because it is more readily available and less expensive than 3He. New 129Xe generators, such as the XeBox-E10 produced by Xemed (Fig. 10) are currently in development and may make widespread implementation of HP gas imaging feasible in the near future.

In addition to the greater availability and affordability of 129Xe, the physical characteristics of 129Xe provide certain imaging advantages over 3He. Unlike 3He, 129Xe is soluble in tissue and blood, allowing it to be used in imaging of gas exchange at the level of the alveolar capillary bed and provide information about diffusion capacity. This can be performed using a chemical shift saturation recovery method using 129Xe magnetization or using xenon transfer contrast.

**Oxygen-enhanced imaging** O2-enhanced MR imaging was first proposed when shortening of the T1 of lung parenchyma was noted in patients breathing 100% oxygen. Although oxyhemoglobin is diamagnetic, O2 is paramagnetic and it therefore modulates the signal emitted from protons in adjacent fluid and tissues. This dissolved paramagnetic free molecular O2 causes a reduction in the T1 relaxation time in oxygenated tissues. When imaging the lung while a patient is breathing room air, the partial pressure of O2

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**Fig. 4.** Coronal HP 129Xe and 3He ventilation images from 2 patients with CF. Imaging for each patient was completed on the same day. Note that excellent image quality was obtained with both 129Xe and 3He. In subject A, the ventilation defects with the 2 gases are similar. In subject B, the ventilation defects are larger and more conspicuous with 129Xe. This difference observed in subject B is possibly attributable to the different physical properties of 129Xe and 3He gases. All images were acquired at 1.5 T using a single-channel chest RF coil and a low-flip-angle gradient echo (FLASH) pulse sequence. (Adapted from Mugler JP, Altes TA. Hyperpolarized 129Xe MRI of the human lung. J Magn Reson Imaging 2013;37(2):313–31; with permission.)

**Fig. 5.** HP gas diffusion MR imaging. ADC is determined by random Brownian motion of HP gas molecules within the alveoli. When the alveolus is expanded, molecules travel a greater distance, leading to larger ADC values.
within the pulmonary venous and systemic arterial blood (PaO₂) is equal to the partial pressure of O₂ within the alveoli (PAO₂), each measuring approximately 100 mm Hg. However, when a patient breathes 100% oxygen, the alveolar PAO₂ is approximately 600 mm Hg, leading to a 6-fold increase in the concentration of dissolved O₂ in arterial blood. This 6-fold increase results in a reduction in the T₁ relaxation time by approximately 9%, and this change in T₁ relaxation time is used to perform O₂-enhanced MR imaging. Because this is a small change in the T₁ relaxation time, separate sequences are performed with the patient breathing both room air and 100% O₂, allowing for better quantification of signal changes.

MR imaging is performed while the patient wears a nonrebreathing mask or mouthpiece with a nose clamp and alternates between breathing room air and 100% oxygen. A subtraction map is generated, and the difference between the 2 image sets results in the O₂-enhanced ventilation images. T₁-weighted inversion recovery (IR) single-shot turbo spin echo (TSE), HASTE, and rapid acquisition with relaxation enhancement (RARE) sequences are usually used, with TE kept as short as possible. Background subtraction can be optimized by suppressing signal from thoracic fat and muscle using IR HASTE sequences or applying inversion pulses to the surrounding tissues. Imaging can be performed in quiet breathing, but respiratory and cardiac motion can often degrade the quality of the subtracted O₂ ventilation image so respiratory triggering and ECG gating are often helpful.

Because O₂-enhanced MR imaging assesses oxygen delivery at the alveolar level, several studies

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**Fig. 6.** Axial CT and ³He ADC map of a patient after left lung transplant. (A) Axial CT demonstrates hyperexpansion of the native right lung, with a relatively normal transplanted left lung. (B) The ADC map demonstrates increased ADC values within hyperexpanded portions of the native right lung and normal ADC values within the transplanted left lung. (Adapted from Altes TA, Salerno M. Hyperpolarized gas MR imaging of the lung. J Thorac Imaging 2004;19(4):250–8; with permission.)

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**Fig. 7.** Comparison of diffusion imaging using ¹²⁹Xe and ³He. Coronal ADC maps were obtained in 2 healthy individuals and in 2 patients with chronic obstructive pulmonary disease (COPD) using ¹²⁹Xe (2 images on the left) or ³He (2 images on the right). For both gases, the ADC values are relatively low and spatially uniform in the healthy individuals. In contrast, the ADC values for the COPD patients are markedly inhomogeneous and generally increased compared with those for the healthy individuals, particularly in the apices. (Adapted from Mugler JP, Altes TA. Hyperpolarized ¹²⁹Xe MRI of the human lung. J Magn Reson Imaging 2013;37(2):313–31; with permission.)
have demonstrated its usefulness in the evaluation of a large number of pulmonary diseases.\textsuperscript{59–66} Diagnostic studies combining O\textsubscript{2}-enhanced MR imaging and contrast-enhanced perfusion imaging (described in the next section) have been described, and may be well suited to replace nuclear medicine V/Q studies in the future.\textsuperscript{67,68}

**Perfusion evaluation**

Numerous different pulmonary disease processes in both pediatric and adult patients cause alterations in lung perfusion. Perfusion can be evaluated on MR imaging with or without contrast enhancement. Alterations in perfusion can be related to ventilation, as when hypoxic vasoconstriction leads to regional hypoperfusion. Decreases in perfusion can also be independent of ventilation, such as in the case of PE. Perfusion imaging can be performed alone or along with ventilation imaging to create ventilation/perfusion MR imaging.\textsuperscript{31}

**Contrast-enhanced perfusion imaging** Several techniques to image lung perfusion have been described, but the most commonly used method is known as dynamic contrast-enhanced (DCE) imaging.\textsuperscript{69} In this technique, a paramagnetic contrast agent such as gadolinium diethylene-triamine-penta-acetic acid (Gd-DTPA) is administered intravenously and time-resolved dynamic MR imaging is performed. Several imaging sequences have been described, including 3D fast low-angle shot (FLASH), time-resolved echo-shared angiographic technique (TREAT), TRICKS, and time-resolved angiography with interleaved stochastic trajectories (TWIST).\textsuperscript{31,69–71} Dynamic imaging allows for visualization of the contrast as it circulates through the body and diffuses into the extravascular extracellular space of the lung.\textsuperscript{31} Visual assessment of regional perfusion is facilitated by subtraction of the precontrast images from the images obtained during peak enhancement. More sophisticated analyses can also be performed to evaluate the kinetics of contrast enhancement. This can include evaluation of the signal curve and analysis of time to peak enhancement, bolus arrival time, and maximum enhancement.\textsuperscript{72} Statistical analysis and automatic lung segmentation

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**Fig. 8.** Coronal HP \textsuperscript{3}He ADC maps from 2 healthy individuals aged 8.8 years and 27.6 years. The ADC maps of both individuals are relatively homogeneous but the ADC values of the older individual are higher (mean ADC 0.236 cm\textsuperscript{2}/s) than those of the younger individual (mean ADC 0.146 cm\textsuperscript{2}/s), demonstrating the ability of imaging to detect growth of the lung microstructure during childhood. (\textit{Adapted from} Altes TA, Mata J, de Lange EE, et al. Assessment of lung development using hyperpolarized helium-3 diffusion MR imaging. J Magn Reson Imaging 2006;24(6):1277–83; with permission.)

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**Fig. 9.** Coronal HP \textsuperscript{3}He ADC maps from two 9-year-old children: one healthy and the other with a history of preterm birth and severe bronchopulmonary dysplasia (BPD). The healthy child has homogeneous low ADC values (mean ADC 0.17 cm\textsuperscript{2}/s). The child with BPD has markedly increased and heterogeneous ADC values (mean ADC 0.23 cm\textsuperscript{2}/s).
can be applied and percent perfusion per lung region can be estimated. Using the indicator dilution theory, quantitative estimations of pulmonary blood volume, pulmonary blood flow, and mean transit time can be performed.69,73–75 A greater signal-to-noise ratio is achieved on 1.5-T systems compared with 3.0-T systems as a result of higher susceptibility effects at greater magnetic field strengths.76

Most of the research on DCE MR imaging of the lung has been performed in adults to evaluate for PE,77,78 chronic obstructive pulmonary disease,79–81 pulmonary hypertension,82,83 and postoperative lung function,84 but perfusion imaging has also been described in the evaluation of cystic fibrosis in children.85

Non–contrast-enhanced perfusion imaging Using techniques that mark a fraction of blood by selective RF excitation, it is possible to obtain perfusion information without the use of intravenous contrast.86–91 This technique is called arterial spin labeling (ASL). Two ASL techniques called flow-sensitive alternating inversion recovery (FAIR) and flow-sensitive alternating inversion recovery with an extra RF pulse (FAIRER) have been developed, and allow for quantification of pulmonary perfusion.88,91 Detailed descriptions of image acquisition are described elsewhere.82,83 FAIR sequences apply a spatially selective inversion pulse before acquiring one image set and a nonselective inversion pulse before a second image set, and perfusion-weighted images are obtained from the subtraction of the 2 image sets.91,93 FAIRER sequences are slightly different because they apply an additional spatially selective 90° RF pulse followed by a dephasing gradient before or after the inversion pulse.88 A major advantage of ASL is the ability to repeat sequences as many times as needed without the need to wait for contrast clearance or limitation by the maximum volume of contrast that can be administered per day. ASL is particularly sensitive to motion artifacts because it is a subtraction technique, and variation between images can lead to ghosting artifacts and the appearance of bright-dark pairs of blood vessels.91 ECG gating is often used to mitigate these artifacts. Although studies of pulmonary ASL have been largely performed in the adult population, it has potential benefits in older pediatric patients who are able to follow breathing instructions.

SPECTRUM OF THORACIC DISORDERS IN PEDIATRIC PATIENTS

Using the imaging techniques described earlier, MR imaging provides a powerful diagnostic tool for the evaluation of a large number of thoracic disorders in pediatric patients without the use of ionizing radiation. The use of MR imaging in the diagnosis and management of these disorders is described and examples are presented.

Disorders of Lung Parenchyma

Congenital lung malformations

Congenital pulmonary malformations are a heterogeneous group of disorders that affect the lung parenchyma as well as the arterial supply and the venous drainage of the lung. These anomalies include, but are not limited to, bronchial atresia, congenital pulmonary airway malformation (CPAM; formerly known as congenital cystic adenomatoid malformation), and bronchopulmonary sequestration. These lesions are increasingly diagnosed prenatally with ultrasonography and MR imaging94–97; however, they can also present as a cause of respiratory distress in the newborn or as recurrent infection in older children. CT has been the mainstay of postnatal diagnosis and presurgical planning,98–100 but use of MR has been described in the evaluation of congenital pulmonary malformations.101,102
MR imaging with MR angiography is well suited to imaging of bronchopulmonary sequestration, because a region of abnormal lung parenchyma is often easily identified on T2-weighted sequences and an aberrant vessel can be identified on MR angiography (Figs. 11 and 12). Solid and microcystic CPAMs are also easily identified on MR images but macrocystic CPAMs can be more difficult to assess, given the lack of associated signal on MR, and CT is usually required for preoperative planning (Fig. 13). MR evaluation of bronchial atresia has been described and can be diagnosed based on the observation of high signal on T1-weighted and T2-weighted sequences within an atretic bronchus due to impacted mucus, but the associated hyperinflation that is easily identified on radiographs and CT may be more difficult to assess on MR. Ventilation sequences may be helpful in this setting, although this requires further investigation.

A suggested MR protocol for the evaluation of a nonvascular congenital pulmonary malformation includes axial fast relaxation fast spin echo (FRFSE) T2 fat saturation, axial T1 or double inversion recovery (DIR) with breath-hold and ECG gating, coronal FRFSE T2 fat saturation, coronal 3D MR angiography, SPGR with gadolinium, and postcontrast axial and coronal T1 fat saturation using an 8-channel cardiac coil. When evaluating a vascular congenital pulmonary malformation, the addition of axial, sagittal, and coronal oblique fast spin echo (FSE) DIR sequences with breath-hold and ECG gating and contrast-enhanced sagittal 3D SPGR MR angiography is useful.

**Pulmonary infection**

The first-line imaging modality for evaluating pulmonary infection is radiography, but cross-sectional imaging is often needed in cases of immunocompromised patients and complicated pneumonia. A recent prospective study of 40 consecutive pediatric patients evaluated the efficacy of chest MR imaging with fast imaging sequences at 1.5 T for evaluating pneumonia by comparing MR imaging findings with those of chest radiographs. In this study, the investigators found that MR imaging with fast imaging sequences is comparable with chest radiographs for evaluating pulmonary consolidation, bronchiectasis, necrosis, abscess, and pleural effusion often associated with pneumonia in children.

CT has a well-established role in the evaluation of pulmonary infection, but MR is playing an increasing role mainly because of concern about radiation exposure in children. Although CT may detect subtle early changes of pulmonary infection with greater sensitivity, MR has been proved useful in evaluation of abnormalities of the parenchyma, pleura, and lymph nodes in suspected complicated lung infection in children (Fig. 14). A recent prospective study of 71 consecutive pediatric patients investigated the efficacy of thoracic MR imaging with fast imaging sequences without contrast at 1.5 T for evaluating thoracic abnormalities by comparing MR findings with those of contrast-enhanced multidetector computed tomography (MDCT). Gorkem and colleagues found that MR imaging with fast imaging sequences without contrast is comparable with contrast-enhanced MDCT for detecting...

Fig. 11. A 20-month-old male infant with left lower extralobar pulmonary sequestration. (A) Axial T2-weighted fast relaxation fast spin echo with fat saturation. (B) Axial T1-weighted. (C, D) Consecutive axial images from contrast-enhanced CT. (E) Sagittal fast STIR. (F) Coronal contrast-enhanced TRICKS MR angiography. Wedge-shaped mass adjacent to the left lower lobe and superior to the diaphragm demonstrates hyperintensity on T1-weighted and T2-weighted images. Arterial supply from the descending aorta is seen on CT (white arrow) and MR angiography (white arrowhead) and venous drainage to the hemiazygous vein (black arrow) is seen on CT. Venous drainage is not well demonstrated on this MR image.
Thoracic abnormalities in pediatric patients. They suggested that the use of MR imaging with fast imaging sequences without contrast as a first-line cross-sectional imaging study in lieu of contrast-enhanced MDCT has the potential to benefit this patient population because of reduced radiation exposure and intravenous contrast administration.\textsuperscript{114}

A suggested MR protocol for the evaluation of suspected complicated lung infection includes axial T2-weighted, coronal T2-weighted, coronal STIR, and postcontrast axial and coronal fat-suppressed T1-weighted sequences,\textsuperscript{110} although this new research suggests that contrast-enhanced sequences may be avoided in many cases.\textsuperscript{114}

**Neoplasm**

Because primary lung tumors are rare in children, no systematic studies evaluating the use of MR imaging in primary pediatric malignancy have been conducted. The evaluation of pulmonary nodules and pulmonary metastases by MR has been investigated in adults,\textsuperscript{5,115} and there is broad consensus that pulmonary metastases of 5 mm or more can be reliably detected\textsuperscript{103} and animal models have suggested that lesions of 4 mm or more could feasibly be identified using 3D and 2D GRE sequences.\textsuperscript{116} Recently, Gorkem and colleagues\textsuperscript{114} showed that the diagnostic accuracy of MR imaging with fast imaging sequences without contrast is high for detecting pulmonary nodules (>4 mm) in pediatric patients using contrast-enhanced MDCT as the reference standard. Because early identification of even small pulmonary metastasis (<4 mm) is clinically important, contrast-enhanced CT is currently the preferred method for initial evaluation of metastatic disease. However, MR imaging may be used to monitor known pulmonary metastases during therapy or as an alternative to CT when iodinated contrast is contraindicated (Figs. 15 and 16).\textsuperscript{103,117} Such practice has great potential for decreasing overall radiation exposure in pediatric patients who require multiple imaging evaluations.

A proposed MR protocol for the evaluation of pulmonary nodules includes coronal T2-weighted HASTE, axial T1-weighted 3D-GRE (VIBE) during breath-hold, coronal steady-state free precession (SS-GRE, TrueFISP) in free-breathing, and axial

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**Fig. 12.** A 48-day-old female infant with prenatal imaging demonstrating a chest mass, found to have left lower extralobar pulmonary sequestration. (A) Axial T2-weighted FSE with fat saturation. (B) Axial T1-weighted spin echo. (C) Coronal IR FSE. (D) Coronal CEMRA. Wedge-shaped mass adjacent to the left lower lobe and superior to the diaphragm demonstrates hyperintensity on T1-weighted and T2-weighted images. Arterial supply from the descending aorta is seen on MR angiography (white arrow). Venous drainage is not well demonstrated.
Fig. 13. A 6-year-old boy with macrocystic left lower lobe CPAM and right paraspinal complex esophageal duplication cyst. (A) Axial T1-weighted spin echo. (B) Axial T2-weighted FRFSE with fat saturation. (C, D) Axial contrast-enhanced CT in soft tissue and lung windows. Left lower lobe macrocystic CPAM is not as well seen on MR imaging as on CT in lung windows given the large air-filled spaces. However, the fluid-filled right paraspinal esophageal duplication cyst is easily seen on both MR and CT images.

Fig. 14. A 5-year-old girl with recurrent right upper lobe pneumonia. Posterior right upper lobe consolidation and bronchiectasis are seen on CT (A) and are well visualized on MR images (B, C). (Courtesy of Sureyya B. Gorkem, MD, Department of Radiology, Erciyes Medical School, Kayseri, Turkey.)

Fig. 15. A 12-year-old girl with metastatic hemangioendothelioma. Several pulmonary nodules are well seen on MR imaging and CT, including a 10-mm right lower lobe nodule (arrows). (A) Axial T2-weighted FRFSE with fat saturation. (B) Axial contrast-enhanced T1-weighted lung acquisition with volume acceleration. (C) Axial noncontrast CT in lung windows.
T2-weighted STIR (T2-TIRM) in a multi breath-hold technique. When motion artifact is an issue, the T2-weighted STIR sequence can be replaced by a fat-saturated T2-weighted FSE with Propeller acquisition and reconstruction (T2 TSE BLADE), which significantly reduces motion artifact although the acquisition time is longer.\(^5\) Contrast-enhanced sequences may not improve nodule detection but they are generally preferred for clearer depiction of vessels, hilar structures, and pleural enhancement. Therefore, a postcontrast 3D-GRE (VIBE) sequence has also been recommended.\(^5\)

**Interstitial lung disease**

Over the past 3 decades, CT has served as the primary imaging modality for the assessment of interstitial lung disease (ILD) in both adults and children.\(^{117}\) With recent advances in MR imaging, it is now comparable with CT in many instances. However, a limited number of studies investigating MR in ILD have been performed and no systematic studies have been performed on children.

Findings in diseases of the lung interstitium involve abnormalities of the interstitium itself and/or the airspaces.\(^{103,117}\) Airspace disease manifests as a hyperintense signal on T2-weighted sequences adjacent to hypointense air-filled normal lung parenchyma. This is akin to ground glass opacities seen on CT when the pulmonary vascular markings are not obscured by the T2 signal\(^{117–119}\) and akin to consolidation seen on CT when the vasculature is obscured by the T2 signal.\(^{110,117,120}\) Interstitial abnormalities also appear as hyperintensity on T2-weighted images but are seen as curvilinear bands, nodules, reticulation, or parenchymal distortion (Fig. 17).\(^{117,121–125}\) Given its superior contrast resolution over CT, MR imaging has the potential to differentiate active interstitial inflammation from fibrosis, which has significant clinical implications for predicting treatment response in ILD.

**Fig. 16.** A 14-year-old boy with lymphoma. Several pulmonary nodules are well seen on MR imaging and subsequent CT performed 4 days later, including a 13-mm right upper lobe nodule (arrows). Left lung collapse seen on MR imaging had resolved by the time of CT. (A) Axial contrast-enhanced T1-weighted. (B) Coronal IR FSE. (C, D) Axial and coronal contrast-enhanced CT in lung windows.

**Fig. 17.** A 6-month-old girl with pulmonary lymphangiectasia and persistent tachypnea after left chylothorax drainage. Coronal T2-weighted FRFSE with fat saturation demonstrates diffuse bilateral linear hyperintensity within the interstitium, which is greater on the right, and trace left pleural effusion.
Increased T2 signal within the interstitium has been shown to correlate with active inflammation, whereas an isointense signal correlates with fibrosis. DCE perfusion MR imaging has also been used to evaluate active inflammation in ILD, and earlier peak enhancement times were shown to correlate with disease activity.

The previously described standard MR protocol for evaluation of lung parenchyma is also well suited for the evaluation of ILD. Imaging on a 3-T system is preferred. DCE perfusion sequences can also be added to evaluate for active inflammation.

Disorders of the Large Airways

Disorders of the pediatric large airway can be divided into static and dynamic processes. The static processes account for most airway abnormalities and include anomalies of tracheobronchial branching, bronchial atresia, congenital tracheal stenosis, neoplasm, infection, and acquired tracheobronchial stenosis from previous instrumentation or surgery. MR imaging is well suited to the evaluation of these disorders. The main dynamic disease process of the pediatric airway is TBM, which is characterized by weakening of the tracheal and bronchial walls or supporting cartilage leading to excessive collapse of the airway during expiration. MR imaging is also well suited to the evaluation of this dynamic disease process, although specific patient preparation and MR imaging sequences are required (see Fig. 1; Fig. 20).

**Static large airway abnormalities**

MR imaging is well suited to evaluate the static large airway abnormalities described earlier because the air-filled tracheobronchial tree appears as a low signal outlined by the higher signal tracheal and bronchial walls, mediastinum, and lungs. Airways smaller than 3 mm in diameter cannot be reliably visualized unless filled with hyperintense material. This is particularly important in the evaluation of young children; MR imaging has been shown to reliably depict airways to the first subsegmental level in regions without artifact, although it is more limited in areas with cardiac pulsation and motion artifact.

The previously described standard non–contrast-enhanced protocol for evaluation of lung parenchyma with the addition of a 3D SPGR sequence is well suited for the evaluation of anomalies of tracheobronchial branching, bronchial atresia, congenital tracheal stenosis, and acquired tracheobronchial stenosis. The addition of a contrast-enhanced 3D GRE (VIBE) sequence is useful when evaluating neoplasms, infection, and inflammation affecting the large airway.

**Dynamic large airway abnormalities**

TBM is a relatively common dynamic disease process of the pediatric large airway. Because the major imaging finding in this disorder is excessive collapse of the airway during expiration, imaging must be performed at end expiration in addition to end inspiration (see Fig. 20). Dynamic imaging obtained during breathing can be used to visualize airway collapse. Until recently, CT
has been the mainstay of evaluation\textsuperscript{12–16} although emerging techniques in spirometer-controlled MR imaging provide a method for dynamic evaluation of the airway without the use of ionizing radiation. This technique, described in detail previously, may play an important role in the evaluation of TBM in the near future.

**Fig. 19.** A 16-year-old girl with a history of VACTERL association (vertebral defects, anal atresia, cardiac defects, tracheoesophageal fistula, renal anomalies, and limb abnormalities) with tracheoesophageal fistula and left pulmonary artery sling leading to severe subglottic stenosis, after tracheal transplant and left pulmonary artery plasty. The tracheal transplant is diffusely thickened, edematous, and hyperenhancing (arrows). Reactive right paratracheal and hilar lymph nodes are also noted (arrowheads). (A) Axial T2-weighted FRFSE with fat saturation. (B) Axial ECG-gated T1-weighted. (C) Axial contrast-enhanced ECG-gated T1-weighted with fat saturation. (D) Coronal T2-weighted FRFSE with fat saturation. (E) Coronal contrast-enhanced ECG-gated T1-weighted with fat saturation.

**Diseases of Small and Medium Airways**

Two major diseases of the small and medium airways in children are asthma and cystic fibrosis (CF). These diseases lead to characteristic changes within the airway including narrowing, wall thickening, smooth muscle contraction, and/or dilation. Functional and morphologic evaluation

**Fig. 20.** Patient with TBM. Images obtained during inspiration (A) and expiration (B) demonstrate dynamic tracheal collapse (arrow) during expiration. (A) Spirometry-gated 3D SPGR during inspiration. (B) Spirometry-gated 3D SPGR during expiration.
of these changes can be evaluated using MR techniques including standard nonenhanced and contrast-enhanced sequences, HP gas imaging, and O₂-enhanced imaging.

**Asthma**

Asthma is a chronic inflammatory disorder of the lungs that is fairly common in the pediatric patient population. Asthma affects small and medium airways and causes smooth muscle hyperresponsiveness and hypertrophy, increased mucous production, and subepithelial fibrosis. Many of these findings are not evident on standard MR sequences, but investigational techniques in HP gas imaging using ³He and ¹²⁹Xe and O₂-enhanced MR have shown promise in the evaluation of patients with asthma.

During HP gas MR imaging, ³He or ¹²⁹Xe is inhaled and acts as a positive contrast agent, filling the airspaces. When inhaled by a healthy patient, the HP gas distributes evenly within the lung (see Fig. 3). When the HP gas is inhaled by a patient with obstruction of medium and small airways caused by asthma, the airspaces distal to the obstruction do not fill with the positive contrast agent. Therefore, the lungs of healthy patients demonstrate a uniform high signal, whereas the lungs of patients with asthma show wedge-shaped regions of low signal intensity (Fig. 21). ⁴⁶,⁴⁷,⁴⁸,⁴⁹,⁵⁰,¹²⁹–¹³⁵ In patients with asthma, these defects have been shown to increase with provocation by exercise or administration of a bronchoconstrictor (methacholine) and decrease with albuterol ¹³³,¹³⁴,¹³⁶ (Figs. 22 and 23) and often persist after symptoms have resolved. ¹³⁶ Using fast acquisition techniques, ventilation images can be obtained in nonsedated infants and young children (Fig. 24). Ventilation imaging with ³He and ¹²⁹Xe operate on this same principle; however, ¹²⁹Xe has the additional property of being soluble in tissue and blood. Therefore, ¹²⁹Xe has the potential to evaluate gas delivery and transport within the lung (Fig. 25). ³³,³⁴,³⁶,⁴³,⁴⁵,⁴⁷,⁴⁹,⁵⁰ Recent advances in ¹²⁹Xe production technology ⁴⁴ may allow this investigative technique to gain more widespread use in the evaluation of asthma in the future.

O₂-enhanced MR imaging is another investigational technique that uses the paramagnetic properties of O₂ to image oxygen delivery at the alveolar level. In asthmatics, obstruction of small and medium airways leads to patchy areas of lower oxygenation which appear as patchy regions of low signal on O₂-enhanced MR images (Fig. 26). ⁶ This technique has demonstrated usefulness in the assessment of asthma in adult patients ⁶⁶ and may play a role in the evaluation of asthma in pediatric patients in the future.

**Cystic fibrosis**

CF is a multisystem disorder caused by a mutation of the CFTR gene that results in abnormal viscosity of mucous and impaired mucociliary clearance. Recent progress in the management of CF has led to a significant increase in the life expectancy of patients with CF but it remains one of the

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**Fig. 21.** HP ³He MR lung ventilation imaging in a patient with asthma. Images obtained at variable forced expiratory volume in first second of expiration (FEV₁) demonstrate numerous regions of signal hypointensity reflecting regions of hypoventilation, which increase as FEV₁ decreases.
most frequent lethal inherited diseases in the United States and Europe. Lung involvement is the main cause of morbidity and mortality,\textsuperscript{137} and imaging findings can include air trapping, bronchiectasis, bronchial wall thickening, mucus plugging, centrilobular tree-in-bud nodules, and superimposed infection.\textsuperscript{138} CT is considered the gold standard for evaluation of CF,\textsuperscript{139–141} but advances in MR imaging have allowed it to play an increasing role.\textsuperscript{142}

Previously described standard T1-weighted and T2-weighted nonenhanced and contrast-enhanced MR sequences used for the evaluation of lung parenchyma\textsuperscript{4} have variable accuracy in the evaluation of bronchiectasis and bronchial wall thickening. The accuracy depends on the bronchial level, bronchial diameter, wall thickness, wall signal, and signal within the lumen.\textsuperscript{6} Central bronchi and bronchiectasis are well visualized but bronchi at the third to fourth generation are not as well seen.\textsuperscript{142} T2 prolongation within the bronchial walls and enhancement on postcontrast imaging can be seen and are related to edema and inflammation. Mucus plugging is well demonstrated to the level of small peripheral airways on T2-weighted sequences and can be differentiated from T2 hyperintense edematous bronchial walls based on lack of enhancement.\textsuperscript{142} Consolidation is also well visualized on T2-weighted sequences (see Figs. 14; 27).\textsuperscript{112,142}

HP gas, O\textsubscript{2}-enhanced, and DCE perfusion MR imaging have also been investigated in the evaluation of CF. Airway obstruction leads to ventilatory defects on \textsuperscript{3}He imaging (see Figs. 4; 28),\textsuperscript{143,144} regions of decreased oxygenation on O\textsubscript{2}-enhanced imaging,\textsuperscript{60} and perfusion defects are seen within these regions as a result of reflex hypoxic vasoconstriction or tissue destruction.\textsuperscript{85} With increased investigation, it is anticipated that MR imaging will play a larger role in the evaluation of patients with CF\textsuperscript{6,142} in the future.

### Abnormalities of the Thoracic Vasculature

Common indications for imaging of the thoracic vasculature in children include vascular anomalies
such as vascular rings and slings and partial and total anomalous pulmonary venous connection (PAPVC and TAPVC), lesions with associated abnormal vascular supply such as bronchopulmonary sequestration (see Figs. 11 and 12) and scimitar syndrome, and PE. By using nonenhanced and contrast-enhanced techniques, these entities are well evaluated with MR imaging.

Vascular rings and slings
Vascular rings and slings are causes of respiratory distress and dysphagia in children that are often treated surgically.\textsuperscript{145} Entities include double aortic arch, right aortic arch with aberrant left subclavian artery with left ligamentum arteriosum, right aortic arch with mirror-image branching and right (retroesophageal) ligamentum arteriosum, left aortic

Fig. 24. Successive coronal HP \textsuperscript{3}He MR ventilation images from a nonsedated, marginally cooperative 4-year-old child with asthma demonstrates multiple small ventilation defects throughout the lungs (eg, arrows). This spiral-based sequence has an acquisition time of less than 0.15 seconds per slice, which is adequate to freeze lung motion.

Fig. 25. Direct imaging of dissolved \textsuperscript{129}Xe in the human lung. (A) Three-dimensional acquisitions depicting gas-phase \textsuperscript{129}Xe in the lung airspaces (left side of each section) and dissolved-phase \textsuperscript{129}Xe in the tissue and blood (right side of each section) from a healthy individual (top) and a patient with mild (GOLD stage 1) COPD (bottom). Although the signal intensity distributions for the gas-phase and dissolved-phase components were generally uniform for the healthy individual, except for noticeably higher dissolved-phase signal intensity in the posterior portion of the lung, both gas-phase and dissolved-phase components showed nonuniform signal distributions in the patient with COPD, with some regions of mismatch between corresponding gas-phase and dissolve-phase signal variations. Acquisition parameters are described in Ref.\textsuperscript{36} (B) Maps showing the ratio of dissolved-phase to gas-phase \textsuperscript{129}Xe in the healthy individual (top row) and the patient with COPD (middle row), and showing the ADC for \textsuperscript{129}Xe (b values of 0 and 10 s/cm\textsuperscript{2}) for the patient with COPD (lower row). In the anterior portion of the lung, the ratio of dissolved-phase to gas-phase \textsuperscript{129}Xe for the patient with COPD was substantially higher than that for the healthy individual. Regions of relatively low ratio values for the patient with COPD were generally associated with increased ADC values (eg, arrowheads). (Adapted from Mugler JP, Altes TA. Hyperpolarized \textsuperscript{129}Xe MRI of the human lung. J Magn Reson Imaging 2013;37(2):313–31; with permission.)
Fig. 26. Oxygen-enhanced coronal MR images in a normal patient (A) and a patient with severe asthma (B). In the normal patient, the $O_2$-enhanced signal is uniform throughout the lungs. In the patient with severe asthma, the $O_2$-enhanced signal is diffusely decreased with patchy regions of more decreased signal in the right lower lobe and left midlung.

Fig. 27. MR imaging and CT in 3 patients with CF. (A, B) Axial T2-weighted FSE free-breathing MR imaging (A) and axial noncontrast CT in lung windows demonstrate bilateral upper lobe bronchiectasis and bronchial wall thickening. (C, D) Axial T2-weighted BLADE PD + navigator MR imaging and noncontrast CT in lung windows demonstrate bilateral bronchiectasis, bronchial wall thickening, and left upper lobe consolidation. (E, F) Axial T2-weighted BLADE PD + navigator MR imaging and noncontrast CT in lung windows demonstrate bilateral bronchiectasis, bronchial wall thickening, and bilateral perihilar consolidation.
arch with aberrant right subclavian artery, left aortic arch with right descending aorta and right ligamentum arteriosum, anomalous innominate artery, cervical aortic arch, and pulmonary artery sling. Vascular rings and slings can be reliably identified using nonenhanced MR angiography or CEMRA (Fig. 29).

Suggested protocols include basic T1-weighted and T2-weighted sequences described in detail earlier, ECG-gated black blood SSFSE with DIR, bright blood 2D or 3D SSFP, and MR angiography sequences with or without contrast. Noncontrast MR angiography can be performed using ECG-gated high-resolution free-breathing 3D double-slab fast imaging with steady precession MR angiography (3D FISP MRA) sequences, and are preferable in nonsedated less cooperative patients in whom motion artifact may necessitate multiple image acquisitions. CEMRA is obtained using an ultrafast 3D gradient echo pulse

Fig. 28. Hyperpolarized $^3$He MR lung ventilation imaging in 3 patients with CF causing mild (A, FEV$_1$ = 89%), moderate (B, FEV$_1$ = 67%), and severe (C, FEV$_1$ = 34%) respiratory disease. Wedge-shaped regions of hypointensity increase in number and size as disease severity increases.

Fig. 29. An 11-month-old girl with vascular ring due to a double aortic arch. (A, B) Two contiguous axial proton density-weighted TSE images of the upper chest. (C) Sagittal proton density-weighted TSE image of the upper chest. (D) Lateral fluoroscopic image from barium swallow. MR imaging and fluoroscopic images demonstrate a double aortic arch characterized by a right aortic arch (white arrow) and a partially atretic left arch giving rise to left common carotid (white arrowhead) and subclavian arteries (black arrow). The vascular ring causes a mass effect on the esophagus (black arrowhead).
sequence with short TE and TR (TE/TR/\(\alpha\) = 0.9/2.3 ms/25° or TE/TR/\(\alpha\) = 1.0 m/2.2 ms/40°) during and after the intravenous injection of 0.2 mmol/kg body weight Gd-DTPA at a rate of 2 mL/s using an automatic power injector.\(^{26}\) CEMRA requires a breath-hold of approximately 15 seconds and is therefore more suitable for intubated and cooperative older patients (>6 years).

**Partial anomalous pulmonary venous connection**

In PAPVC, 1 or more (but not all) of the pulmonary veins is abnormally connected to a systemic vein. Depending on the degree of shunting, hemodynamic sequelae can develop as a result of increased pulmonary circulation and can lead to pulmonary hypertension and right heart failure. PAPVC can be associated with several other anomalies including pulmonary developmental anomalies in the spectrum of congenital pulmonary venolobar syndrome (including scimitar syndrome and bronchopulmonary sequestration) and sinus venosis defect. In TAPVC, all the pulmonary veins are abnormally connected to a systemic vein. CEMRA is an excellent imaging test for the evaluation of PAPVC and TAPVC (see Fig. 18; Fig. 30) and several studies have shown CEMRA to be a sensitive and specific modality for the diagnosis of PE in adults (Fig. 31),\(^{150–153}\) although these findings were not reproduced in a large multicenter study (PIOPED III).\(^{154}\) Therefore, MR angiography should only be considered for the diagnosis of PE in cases when contrast-enhanced MDCT is contraindicated. For these patients, a 2-step protocol has been suggested, combining noncontrast and contrast-enhanced MR techniques.\(^{3}\)

The suggested protocol begins with a free-breathing TrueFISP sequence\(^{21,153}\) acquired in 2 or 3 planes in the first 5 minutes of imaging. Kluge and colleagues\(^{153}\) report that this technique has a sensitivity of 85% and a specificity of 98% for the detection of central PE. If a central PE is identified, the examination can be stopped and the patient can be immediately referred for treatment. If no PE is identified, the protocol can be continued with contrast-enhanced sequences, including DCE perfusion\(^{77,78,153,155}\) sequences and CEMRA of the pulmonary arteries using a fat-suppressed 3D-FLASH sequence with breath-hold.\(^{153}\) Kluge and colleagues\(^{153}\) report that this combined protocol has a sensitivity of 100% and specificity of 93% for the detection of PE. The addition of MR ventilation imaging may also be useful in the diagnosis of PE.\(^{156–160}\)

**Pulmonary embolism**

The current reference standard technique to diagnose PE is contrast-enhanced MDCT.\(^{149}\) However, given the significant radiation exposure associated with CT, MR angiography has been investigated as an alternative. Several studies have shown CEMRA to be a sensitive and specific modality for the diagnosis of PE in adults (Fig. 31),\(^{150–153}\) although these findings were not reproduced in a large multicenter study (PIOPED III).\(^{154}\) Therefore, MR angiography should only be considered for the diagnosis of PE in cases when contrast-enhanced MDCT is contraindicated. For these patients, a 2-step protocol has been suggested, combining noncontrast and contrast-enhanced MR techniques.\(^{3}\)

**FUTURE DIRECTION**

Recent advances in MR imaging have allowed for its increased use in the evaluation of thoracic diseases of children. In the future, MR imaging may replace CT for many indications and reduce children’s exposure to ionizing radiation. Because MR imaging is more susceptible to motion artifacts than CT, advances in fast scanning techniques and cardiac and respiratory gating continue to improve the diagnostic quality of thoracic MR imaging. With further study and more widespread availability, DCE perfusion, O2-enhanced imaging,
and HP gas MR imaging may play an increased role in the evaluation of pediatric thoracic diseases including asthma, CF, and PE in the future. New advances in CEMRA using vastly undersampled imaging with projection sequences, which produce 3D data sets by using spherical k-space coverage, have been described in cardiac imaging\textsuperscript{161} and show great promise in imaging of the pulmonary vasculature in the future. Additional newer techniques using Fourier decomposition MR imaging allow for ventilation and perfusion scanning without intravenous or inhaled contrast agents and are in the early stages of development.\textsuperscript{157,162–164} With these and other advances, MR imaging will continue to play an increasing role in the evaluation of pediatric thoracic disease.

SUMMARY

Mainly as a result of concern about the effects of ionizing radiation in children\textsuperscript{1,2} MR imaging has been increasingly used for evaluating pediatric disease in recent years. Adoption of MR imaging for imaging diseases of the thorax has lagged behind MR imaging in other organ systems because of the technical challenges posed by low proton density within the lungs, magnetic susceptibility differences at lung-air interfaces, and respiratory and cardiac motion. However, along with appropriate use of sedation and patient preparation, new techniques in fast scanning, respiratory triggering, spirometer control, ECG gating, MR angiography with and without contrast, O\textsubscript{2}-enhanced imaging, and HP gas imaging allow MR imaging to be used to evaluate many pediatric thoracic diseases. Understanding proper MR techniques and the characteristic MR imaging appearance of various thoracic diseases in pediatric patients is essential to arrive at early and accurate diagnoses, which, in turn, leads to optimal patient care.

REFERENCES


