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Pediatric MRI of the Brain: A Primer

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Drs Patra, Lancaster, Hogg, and Carpenter have disclosed no financial relationships relevant to this article. This commentary does not contain a discussion of an unapproved/investigative use of a commercial product/device.

Educational Gap
Because of recent advances in magnetic resonance imaging (MRI) techniques, pediatricians should be aware of the different modalities and their unique advantages and appropriateness in different clinical situations.

Objectives
After completing this article, readers should be able to:
1. Understand the pros and cons of MRI and computed tomography of the brain.
2. Know the basic principles of MRI and its different image modalities.
3. Be aware of the appropriateness of different modalities in specific clinical situations.

Introduction
Magnetic resonance imaging (MRI) is based on the absorption and emission of radiofrequency energy by hydrogen protons whose spin is influenced by changing magnetic fields (0.3 to 1.5 T). Unlike computed tomography (CT), there is no radiation exposure.

T1-weighted images cause fat (eg, myelin in white matter) to appear bright and water (eg, cerebrospinal fluid [CSF] or edema) to appear dark on this sequence. The gray-white interfaces of the brain are well depicted on these sequences, especially if with the images are thinly sliced. T2-weighted images cause water (eg, CSF and edema) to appear bright and fat to appear dark. The MRI-based intravenous contrast agents (eg, gadolinium) are frequently used in T1-weighted images (Fig 1A and B) to make serum appear bright. The blood-brain barrier typically serves to limit the passage of many molecules out of the blood vessels. If disease processes break down this barrier (such as infection, tumors, or inflammation), intravenous contrast agents can cross into the brain, causing areas of contrast entry to appear very bright.

MRI vs CT
MRI and CT are complementary diagnostic tools with mutually distinct advantages and disadvantages. CT can be performed quickly and is preferred in cases of trauma and emergency circumstances. CT is more sensitive for detecting calcification and better delineates cortical bone. CT angiography has a better resolution compared with magnetic resonance angiography; however, the latter has the advantage of not absolutely requiring the use of contrast agents. MRI cannot be performed in claustrophobic patients and those with ferromagnetic medical devices, such as pacemakers. Further, MRI takes longer to perform and might require sedation, precluding its use in emergency situations. However, for evaluating posterior fossa disease, white matter disease, temporal lobe epilepsy, and vascular diseases, MRI is preferable to CT. In this article, we present some common pediatric case vignettes that illustrate the role of brain MRI to acquaint the reader with the common modalities of MRI.

Case 1
A 7-year-old girl with a history of migraine headaches presented with a head tilt to the left and worsening headaches. Optic disc edema was found on ophthalmoscopy. A brain

Abbreviations
ADHD: attention-deficit/hyperactivity disorder
CSF: cerebrospinal fluid
CT: computed tomography
DWI: diffusion-weighted magnetic resonance imaging
FLAIR: fluid-attenuated inversion recovery
fMRI: functional magnetic resonance imaging
MRI: magnetic resonance imaging
MRV: magnetic resonance venography
NAA: N-acetylaspartate
SDH: subdural hematoma

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MRI was performed, which revealed a large heterogeneous intermediate signal mass that filled and obstructed the fourth ventricle on the axial T2-weighted images at the level of the fourth ventricle (Fig 2). She underwent surgical resection, and the histologic diagnosis was medulloblastoma. Apart from sparing the effects of radiation, MRI is superior to CT in delineating tumor extent, spread, mass effect, vascularity, necrosis, and edema. T2-weighted sequences are sensitive for the detection of tumor and edema.

Case 2
A 6-year-old girl presented with swelling of her right eye. She had a history of sinusitis. Her right eye was swollen and erythematous, she had difficulty opening her right eye, and she had double vision with all gazes. Clinical findings included proptosis, ptosis, restriction of ocular motility, ocular pain, and chemosis. Laboratory tests revealed neutrophilic leukocytosis and elevated C-reactive protein. Head MRI was performed. Coronal postcontrast T1-weighted imaging revealed inflammation in the right orbit with diffuse stranding in orbital fat, enhancing myositis of the inferior and medial rectus muscles (Fig 3).

Orbital cellulitis is an infection of the soft tissue posterior to the orbital septum, whereas preseptal cellulitis affects anterior to the orbital septum. The former is distinguished from the latter by the presence of proptosis, chemosis, ophthalmoplegia, or decreased visual acuity. MRI is superior to CT when there is suspicion of intracranial extension, optic nerve involvement, and cavernous sinus thrombosis because MRI is better for discerning soft tissue disease. Gadolinium is a paramagnetic contrast agent that prolongs the spin of water protons, resulting in postcontrast enhancement of areas of inflammation on T1-weighted imaging. The most sensitive technique for demonstrating orbital infection is postgadolinium, fat-suppressed T1-weighted imaging.

Case 3
A 16-year-old girl presented to the emergency department with a chief symptom of “vision loss in right eye.” She denied eye pain, diplopia, photophobia, or headache.

Figure 1. T1-weighted image at the level of midbrain. A. The cerebrospinal fluid (CSF) appears dark. B. The CSF appears bright. Note the gray and white matter differentiation in the 2 images. The anatomical structures identified here are the caudate nucleus (i), lenticular nuclei (ii), thalamus (iii), frontal horn of lateral ventricle (iv), and atria of the lateral ventricle (v).

Figure 2. Axial T2-weighted image at the level of the fourth ventricle shows a large heterogeneous intermediate signal mass (blue arrow) that fills and obstructs the fourth ventricle.

Figure 3. Coronal postcontrast T1-weighted image shows inflammation in the right orbit with diffuse stranding in orbital fat, enhancing myositis of the inferior and medial rectus muscles (solid yellow arrow indicates the right inferior rectus; solid blue yellow indicates the right medial rectus muscle).
Her medical history was unremarkable. Visual acuity was normal in the left eye (20/20); however, it was decreased in the right eye (20/200). Her right pupil constricted in response to consensual but not to direct light (ie, deafferented pupil). Bilateral fundi appeared normal. MRI of the brain revealed a normal-appearing left optic nerve. The left optic nerve was round with distinct borders and was appropriately surrounded by CSF as demonstrated by T2-weighted fluid-attenuated inversion recovery (FLAIR) imaging. The right optic nerve, however, had poorly defined borders, suggesting an inflammatory process. The inflamed right optic nerve also enhanced with gadolinium administration (Fig 4).

Given the patient’s visual disturbance and the evidence of optic nerve inflammation on MRI, optic neuritis was suggested as a diagnosis. Other MRIs obtained revealed demyelination in the pons and cerebellum. The presence of CSF oligoclonal bands supported multiple sclerosis as the diagnosis.

FLAIR is an extremely useful technique in brain imaging. Like conventional T2-weighted imaging, edema appears bright, but this technique nulls (or makes dark) CSF signal. FLAIR is a sensitive technique for displaying demyelination within the brain, thus clearly revealing lesions in proximity to CSF, such as periventricular plaques in multiple sclerosis. The technique is accomplished via a relatively long inversion time to allow the longitudinal magnetization of CSF to return to the null point preceding the conventional spin echo imaging. It also has a tremendous role in early detection of cortical gray matter infarcts. The cortical gray matter is vulnerable to ischemia because of its high metabolic activity. However, cortical gray matter immediately adjacent to CSF within the sulci makes infarction hard to delineate when this area undergoes conventional imaging sequences that emphasize fluid signal. FLAIR suppresses the CSF signal and makes the cortical or periventricular area more conspicuous.

Case 4
A 3-month-old boy was admitted to the pediatric intensive care unit for bilateral subdural hematomas (SDHs) and concern for intentional trauma. Per his parents, he had emesis for 24 hours and had been unable to keep formula down. He also had 2 episodes of arm stiffening and breath holding followed by agitation and crying. Neurologic examination revealed an enlarged head circumference, dilated scalp veins, and a bulging anterior fontanel. He had brisk tendon reflexes. Brain MRI FLAIR images revealed localizing tissue loss in the right parietal region from an older injury and 2 SDHs of different densities, with the more acute-appearing SDH on the left and the more subacute SDH on the right (Fig 5).

The presence of SDHs of varying ages and of skull fractures, which are depressed or multiple or diastatic or involve multiple or nonparietal bones, is a key neuroimaging finding that is consistent with the diagnosis of intentional trauma. CT is the modality of choice to detect acute hemorrhages and skull fractures. MRI is superior to CT in detecting extra-axial hemorrhages, diffuse axonal injury, and early recognition and prognostication of parenchymal injury. SDHs over the falx, posterior fossa, and tentorium are more characteristic of intentional trauma. (1) T2-weighted gradient echo MRI enhances the sensitivity for recognizing acute bleeds and old shear bleeds. Diffusion-weighted imaging (DWI) is also helpful for revealing early and progressive edema. Of note, bleeding diathesis, birth injury, inborn errors of metabolism (such as glutaric academia type 1 and Menkes disease), lymphohistiocytosis, infection, and unintentional trauma can have similar appearance with DWI. DWI and its uses are further described in case 6.

Case 5
A 4-year-old previously healthy girl was admitted for left-sided weakness and increased somnolence. A week before presentation, she had severe gastroenteritis. Her oral intake was drastically reduced, and she had presented to a local emergency department 2 days earlier with persistent

Figure 4. The left optic nerve (solid yellow arrow) is round with distinct borders and is appropriately surrounded by cerebrospinal fluid as demonstrated by T2-weighted imaging. The right optic nerve (solid blue arrow), however, has poorly defined borders, suggesting an inflammatory process.
vomiting. On the day of her presentation, she was unable to walk. Her vital signs were stable. On examination, she was drowsy. She had left-sided upper motor neuron facial weakness. Her muscle strength in the left upper and lower extremities was 0/5 and 1/5, respectively, and she had a positive Babinski sign. The rest of her examination findings were unremarkable. Her head CT was unremarkable. MRI and magnetic resonance venography (MRV) of the brain demonstrated a large filling defect, occluding and occupying the superior sagittal sinus and medial portion of both transverse sinuses (Fig 6). A conventional head MRI revealed venous infarctions in the left parietal and frontal areas without any hemorrhage. Her coagulation profile was normal. She was treated with intravenous heparin and fluids. Her weakness improved gradually, and subsequent MRV revealed restoration of normal contrast enhanced filling of sagittal and both transverse sinuses (Fig 6).

MRV is the optimal noninvasive technique of delineating cerebral venous anatomy. Time-of-flight, phase-contrast angiography, and contrast-enhanced MRV are the means commonly used to evaluate the cerebral venous structures, commonly the superior sagittal, transverse, sigmoid, and straight sinuses. MRI and MRV are important for demonstrating venous occlusion and its consequences, infarction, and edema. Of note, a thrombus in its subacute phase can be recognizable as a high signal on a T1-weighted scan, thereby making MRV unnecessary to perform for a suspected clot.

Case 6
A term infant developed right-sided clonic seizures on her second day of life. The pregnancy was well supervised,

Figure 5. Fluid-attenuated inversion recovery image localizing tissue loss in right parietal region from an older injury and 2 different densities of subdural hematoma (more acute appearing on the left and subacute on the right).

Figure 6. A. Magnetic resonance venography (MRV) reveals large filling defect that occludes and occupies the superior sagittal sinus (broken blue arrow) and medial portion of both transverse sinuses (broken yellow arrows). B. On the right, coronal MRV with contrast reveals restoration of normal contrast enhanced filling of sagittal (solid blue arrow) and both transverse sinuses (solid yellow arrows).

Figure 7. Coronal T2-weighted image shows loss of gray white differentiation and swelling in the posterior cerebral artery territory on the left side with ventricular effacement secondary to swelling.
and her delivery was uneventful. Her physical examination findings were normal on the first day of life. Maternal drug screen result was negative. Metabolic profile, blood cell count, transfontanel ultrasonography, and CSF study results were normal. A head MRI was performed. Coronal T2 revealed left-sided loss of gray white differentiation and swelling in the region of the posterior cerebral artery with obscuring of the ventricular surface (ventricular effacement) (Fig 7).

The hyperintense signal in the posterior cerebral artery region on DWI and the hypointense signal in the same distribution on apparent diffusion coefficient imaging confirmed the presence of restricted diffusion characteristics of an evolving acute infarction (Fig 8).

By disrupting the cellular metabolism and Na⁺/K⁺ adenosine triphosphatase pump, ischemia results in loss of transmembrane ionic gradients, thereby restricting diffusion of water through cellular membranes. DWI was performed by adding 2 strong diffusion-sensitizing magnetic field gradient pulses. DWI depicts recently infarcted brain as a very bright signal. The actual diffusion in the tissue is decreased as seen on apparent diffusion coefficient maps. This period of restricted diffusion can last 5 to 10 days (but sometimes less) in the pediatric population. DWI can detect ischemic stroke within minutes, in contrast to conventional MRI, which may take hours for diagnosis. DWI is invaluable in detecting lesions not usually identifiable with conventional MRI and can distinguish new and old strokes and acute and chronic ones. Because abscesses, parenchymal contusions, and cysts can also demonstrate restricted diffusion, DWI also helps detect brain abscesses and cystic tumors.

Other MRI Modalities

Magnetic resonance spectroscopy monitors biochemical changes in brain tumors, head trauma, stroke, epilepsy, metabolic disorders, and infections. The metabolites predominantly measured are N-acetylaspartate (NAA), creatine, choline, and myo-inositol. NAA, an amino acid found exclusively in neurons, is regarded as a nonspecific marker of neuronal viability. NAA levels are decreased in conditions such as infarction and neuronal inflammation. Lactate is absent in normal brain tissue, and its presence is indicative of anaerobic glycolysis at the cellular level. Elevated lactate levels are associated with ischemia or neurometabolic disorders (with predominant anaerobic
glycolysis). An elevated choline-creatine ratio is suggestive of malignancy. Choline is involved in the synthesis of phospholipid cell membranes; in aggressive neoplasms, choline is elevated because of rapid cell turnover. Creatine, a precursor of adenosine triphosphate, gives a measure of brain energy stores. In high-grade brain tumors, due to increased metabolic activity, creatine is depleted. Figure 9 shows magnetic resonance spectroscopy image from a 16-year-old girl with ischemic stroke in the occipital area. There is a large lactate peak, decreased NAA peak, and maintained choline-creatine ratio. These findings are characteristic of an ischemic stroke.

Functional MRI (fMRI) reveals brain activity by changing magnetization between oxygen-rich and oxygen-poor blood. fMRI is useful for presurgical mapping, epilepsy, stroke, trauma, tumors, language lateralization, and neurobehavioral disorders, such as attention-deficit/hyperactivity disorder (ADHD) and autism. The diagnosis and management of ADHD can be a challenge because diagnosis relies on parents’ and teachers’ reporting of behavioral symptoms that might be biased and subjective. fMRI has shown that in patients with ADHD there is reduced activation of striatum and frontal lobes during tasks that warrant attention. Thus, in the future, fMRI could be useful to diagnose, prognosticate, and treat patients with ADHD.

Children with ventriculoperitoneal shunts for hydrocephalus require subsequent follow-up CT to evaluate shunt integrity, assess ventricle anatomy, and rule out complications. However, multiple lifetime exposure to ionizing radiation is associated with potential risk for carcinogenesis. (2) Single-shot fast-spin echo (quick-brain) MRI can be used in children with shunt-treated hydrocephalus for workup and follow-up in lieu of CT to circumvent radiation exposure. Because of its ability to generate required data with a single excitation impulse, single-shot fast-spin echo is fast and does not require sedation. Multplanar images are obtained in less than a second, reducing the motion artifacts. (3)

MRI vs a Good History and Physical Examination
Although MRI can be significantly informative, a good history and clinical examination are sufficient for diagnosing and managing many clinical situations, such as primary headache (chronic or recurrent headache, including migraine without permanent neurologic signs or signs of increased intracranial pressure), simple syncope, simple febrile seizures, and benign positional vertigo. (4)

Summary
• On the basis of strong recommendation, magnetic resonance imaging (MRI) and computed tomography (CT) are complementary diagnostic tools with mutually distinct advantages and pitfalls. MRI is preferred to CT in posterior fossa disease, white matter disease, temporal lobe epilepsy, and vascular diseases.
• On the basis of strong recommendation, diffusion-weighted imaging is superior to noncontrast CT for diagnosis of acute ischemic stroke in patients who present within 12 hours of symptoms. (5)
• On the basis of strong recommendation, fluid-attenuated inversion recovery MRI is a sensitive technique for displaying demyelination within the brain, especially in lesions near the cerebrospinal fluid, such as periventricular plaques in multiple sclerosis. In clinically isolated syndrome, 3 or more white matter lesions on T2-weighted MRI is highly predictive of future development of clinically definite multiple sclerosis. (6)
• There is insufficient evidence to support or refute neuroimaging in a child presenting with status epilepticus. (7)

References
PIR Quiz Requirements

To successfully complete 2014 Pediatrics in Review articles for AMA PRA Category 1 Credit™, learners must demonstrate a minimum performance level of 60% or higher on this assessment, which measures achievement of the educational purpose and/or objectives of this activity. If you score less than 60% on the assessment, you will be given additional opportunities to answer questions until an overall 60% or greater score is achieved. NOTE: Learners can take Pediatrics in Review quizzes and claim credit online only at: http://pedsinreview.org.

1. An infant in the newborn nursery has just experienced 3 focal seizures of her right arm, yet she appears well and is afebrile. You suspect a neonatal stroke. Among the following, the MOST appropriate brain imaging to establish this diagnosis is:
   A. Computed tomography.
   B. Magnetic resonance angiography.
   C. Magnetic resonance imaging with diffusion-weighted imaging.
   D. Magnetic resonance spectroscopy.
   E. Single-shot fast-spin echo magnetic resonance imaging.

2. You are counseling the parents of a toddler with shunted hydrocephalus. His family is concerned about the long-term effects of radiation exposure used to image the brain for evidence of shunt malfunction. Among the following, you are MOST likely to say:
   A. Computed tomography has a limited radiation exposure, far less than therapeutic radiation, and the couple should not be concerned.
   B. Head ultrasonography should always be used as a screening tool before considering computed tomography.
   C. Magnetic resonance imaging with diffusion-weighted imaging will be useful to distinguish acute from subacute shunt failure.
   D. Magnetic resonance imaging with fluid-attenuated inversion recovery (FLAIR) differentiates cerebrospinal fluid as dark from other water, which appears bright, and FLAIR is an optimal way to diagnose shunt failure.
   E. Single-shot fast-spin echo magnetic resonance imaging is a promising technique to obtain imaging in just seconds without sedation and is optimal to evaluate shunt integrity and assess ventricular anatomy.

3. A 6-year-old presents with progressive occipital headaches, nausea, and vomiting for 2 weeks. Head computed tomography in the emergency department reveals a possible lesion in the posterior fossa. You now request brain magnetic resonance imaging with gadolinium contrast because this contrast will help highlight:
   A. Arachnoid cyst.
   B. Cerebral dysgenesis.
   C. Chiari malformation.
   D. Hydrocephalus.
   E. Tumor.

4. A 15-year-old boy presents to the emergency department with severe headache after striking his head without a helmet while skateboarding. You decide to perform imaging of his head. Among the following, the MOST appropriate modality to detect a skull fracture or acute parenchymal hemorrhage is:
   A. Computed tomography.
   B. Magnetic resonance imaging with diffusion-weighted imaging.
   C. Magnetic resonance spectroscopy.
   D. Single-shot fast-spin echo magnetic resonance imaging.
   E. Ultrasonography.
5. A 16-year-old girl was found to have a right parietal mass with computed tomography. She is scheduled to undergo magnetic resonance imaging, and the radiologist suggests adding spectroscopy to determine the nature of the mass. Among the following, the finding MOST suggestive for tumor on spectroscopy is:

A. Decreased lactate.
B. Decreased phospholipid.
C. Elevated choline-creatine ratio.
D. Elevated creatine.
E. Elevated N-acetyl aspartate.

Parent Resources from the AAP at HealthyChildren.org

- English: http://www.healthychildren.org/English/health-issues/conditions/treatments/Pages/Imaging-Tests.aspx
- Spanish: http://www.healthychildren.org/spanish/health-issues/conditions/treatments/paginas/imaging-tests.aspx

Correction

In the February 2014 Pediatrics in Review article “The Clinician’s Guide to Autism” (PediatrRev. 2014;35(2):62–78, doi:10.1542/pir.35-2-62), there is an error in CME Quiz Question 1. The child’s age should be 4 years old, and the correct answer should be “B. Childhood Autism Screening Test.” The online version of the quiz was resupplied to correct this error. The journal regrets the error.
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