ACR–ASNR–SPR PRACTICE PARAMETER FOR THE PERFORMANCE OF MAGNETIC RESONANCE IMAGING (MRI) OF THE PEDIATRIC SPINE

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PREAMBLE

This document is an educational tool designed to assist practitioners in providing appropriate radiologic care for patients. Practice Parameters and Technical Standards are not inflexible rules or requirements of practice and are not intended, nor should they be used, to establish a legal standard of care[1]. For these reasons and those set forth below, the American College of Radiology and our collaborating medical specialty societies caution against the use of these documents in litigation in which the clinical decisions of a practitioner are called into question.

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The practice of medicine involves the science, and the art of dealing with the prevention, diagnosis, alleviation, and treatment of disease. The variety and complexity of human conditions make it impossible to always reach the most appropriate diagnosis or to predict with certainty a particular response to treatment. Therefore, it should be recognized that adherence to the guidance in this document will not assure an accurate diagnosis or a successful outcome. All that should be expected is that the practitioner will follow a reasonable course of action based on current knowledge, available resources, and the needs of the patient to deliver effective and safe medical care. The purpose of this document is to assist practitioners in achieving this objective.

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1 *Iowa Medical Society and Iowa Society of Anesthesiologists v. Iowa Board of Nursing, 831 N.W.2d 826 (Iowa 2013) Iowa Supreme Court refuses to find that the "ACR Technical Standard for Management of the Use of Radiation in Fluoroscopic Procedures (Revised 2008)" sets a national standard for who may perform fluoroscopic procedures in light of the standard's stated purpose that ACR standards are educational tools and not intended to establish a legal standard of care. See also, Stanley v. McCarver, 63 P.3d 1076 (Ariz. App. 2003) where in a concurring opinion the Court stated that "published standards or guidelines of specialty medical organizations are useful in determining the duty owed or the standard of care applicable in a given situation" even though ACR standards themselves do not establish the standard of care.*

I. INTRODUCTION

This practice parameter was developed collaboratively by the American College of Radiology (ACR), the American Society of Neuroradiology (ASNR), and the Society for Pediatric Radiology (SPR).

Pediatric spinal imaging relies predominantly on magnetic resonance imaging (MRI) for the evaluation, assessment of severity, and follow-up of diseases of the pediatric spine. Ultrasound (US) is still used in neonates younger than 6 months to assess for spinal contents; its utility, however, diminishes significantly afterward because of the lack of an adequate acoustic window [1]. Computed tomography (CT), although disfavored due to its use of ionizing radiation and limited disc and intraspinal evaluation, can be useful in the setting of trauma or in the emergent setting when MRI is not feasible, as an adjunct to evaluate bony anatomy, or for those children who have implanted devices/ferromagnetic materials that are either MR-unsafe or produce significant MR artifacts.

Although a variety of imaging modalities can provide diagnostic information in pediatric patients based on specific clinical indications, MRI is the most sensitive diagnostic test for detecting abnormalities of the spine and adjacent structures. Interpretation of imaging findings benefits from correlation with the patient's history, examination, and physiologic tests. Adherence to the following practice parameter will enhance the probability of detecting such abnormalities.

II. INDICATIONS

A. Indications for pediatric spine MRI include, but are not limited to, the evaluation of:

1. Congenital spine malformations
    a. Spinal dysraphism
        i. Open: non-skin-covered and exposed neural elements
        Myelocele/myelomeningocele and its spectrum of findings
        ii. Closed: skin-covered neural elements
        Cutaneous stigmata—sacral dimple, skin tag, focal hirsutism, focal discoloration, capillary hemangioma, hairy nevus, or hyperpigmented patches

    b. Skeletal abnormalities and dysplasia
        i. Anorectal anomalies
        ii. Scoliosis
        iii. Multiple hereditary exostosis
        iv. Congenital spinal canal stenosis, including foramen magnum narrowing

    c. Systemic syndromes associated with motor, limb, gastrointestinal, cardiac, pulmonary, renal, and/or genitourinary abnormalities
        i. Caudal regression syndrome
        ii. Currarino triad
        iii. VACTERL (vertebral defects, anal atresia, cardiac defects, tracheoesophageal fistula, renal anomalies, and limb abnormalities)

    d. Congenital spinal cord malformation
        i. Concern for tethered cord, including suspicion of a low-lying conus, fatty filum, thickened filum terminale, or intraspinal lesion.
        ii. Suspicious cutaneous findings or high dermal pit or sinus

2. Demyelinating, autoimmune, and inflammatory disorders
    a. Demyelinating disease
        i. Multiple sclerosis (MS)
        ii. Acute disseminated encephalomyelitis (ADEM)
        iii. Neuromyelitis optica spectrum disorder (NMO-SD)
        iv. Myelin oligodendrocyte glycoprotein antibody disease (MOGAD)
        v. Acute inflammatory demyelinating polyradiculopathy (Guillain-Barré syndrome)
        vi. Transverse myelitis

b. Connective tissue disorders (eg, systemic lupus erythematosus)
c. Chronic nonbacterial osteomyelitis (CNO)

3. Infectious conditions
   a. Spinal infection, including disc space infection, vertebral osteomyelitis, and epidural abscess
   b. Spinal cord infection, including abscess and infectious myelitis

4. Vascular disorders

   a. Spinal vascular malformations
   b. Spinal cord infarction

5. Neoplastic and neoplastic-like abnormalities

   a. Intramedullary
   b. Intradural-extramedullary
   c. Intradural leptomeningeal
   d. Extradural soft-tissue and spinal-origin
   e. Paraspinal neoplasia with intraspinal extension
   f. Treatment effects

6. Acquired spinal sequelae

   a. Degenerative disc disease and its sequelae
   b. Trauma
   c. Insufficiency fractures
   d. Spondylolysis and spondylolisthesis

7. Miscellaneous

   a. Spinal abnormalities associated with scoliosis
   b. Syringohydromyelia (multiple etiologies, including idiopathic, Chiari malformations and trauma)
   c. Postoperative fluid collections and soft-tissue changes (extradural and intradural)

II. INDICATIONS

B. Safety Guidelines and Possible Contraindications

See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [2], the ACR Manual on Contrast Media [3], and the ACR Manual on MR Safety [4].

Peer-reviewed literature pertaining to MR safety should be reviewed on a regular basis.

III. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [2].

IV. APPLICATIONS OF MRI

A. Congenital spine lesions

Congenital spine and cord lesions include multiple features of dysmorphology in the pediatric population that start during embryonic development. Open spinal dysraphisms demonstrate externally exposed neural elements through an osseous and cutaneous defect, whereas closed spinal dysraphisms are skin-covered and do not expose the neural elements; instead, cutaneous stigmata predominate the clinical presentation and suggest the underlying dysraphism [5]. In addition, motor, bowel, and bladder dysfunctions may suggest spinal cord tethering

and possible underlying dysraphism as well as skeletal dysmorphologies, such as caudal regression syndrome (that manifests as agenesis of distal spinal column, imperforate anus, genitourinary and renal anomalies, pulmonary hypoplasia, and lower-extremity osseous anomalies) [5]. Identification of other associated anomalies, such as tethering lesions, diastematomyelia, and Chiari malformation, is important [6]. Contrast is not typically indicated for evaluation of congenital abnormalities, although could be added if there is concern for infection or a mass.

IV. APPLICATIONS OF MRI

B. Demyelinating, autoimmune, and inflammatory diseases

Intramedullary diseases can be difficult to differentiate clinically, and MRI plays a key role in making an accurate diagnosis. Accurate MRI interpretation relies on placing imaging findings in context of the clinical onset (immediate, rapid, or prolonged), sensory level, and results of cerebrospinal fluid sampling. Abrupt onset (less than 4 hours to maximal deficit) of nontraumatic myelopathic symptoms is suggestive of either a vascular etiology, such as a cord infarction, or a viral etiology (ie, acute flaccid myelitis). Onset of myelopathic symptoms longer than 4 hours but less than 21 days is a feature of a variety of noninfectious demyelinating or inflammatory conditions including MS, ADEM, NMO, MOGAD, lupus myelitis, and other disorders. Idiopathic transverse myelitis (ITM) is a diagnosis of exclusion made after all testing is completed [7]. . However, some patients may be initially diagnosed with ITM when the final serologic abnormalities are delayed, such as in the case of young children with NMO, where the aquaporin-4 antibodies may not be detected at initial diagnosis but may become positive later. Imaging of the brain is indicated to evaluate for additional and sometimes typical regions of demyelination. Additionally, intravenous contrast is essential for the imaging diagnosis of Guillain-Barre syndrome.

IV. APPLICATIONS OF MRI

C. Infection

Compared with adults, infections of the spine and spinal cord are less common in children. The causative factors include bacterial, viral, fungal, or parasitic organisms. Structural abnormalities, such as dermal sinus tracts, increase the risk of infection. The infectious processes can affect the spinal cord; nerve roots and meninges; epidural space, vertebrae, and the discs [8,9]. Vertebral involvement may result in osteomyelitis, spondylitis, and discitis, often referred to as "spondylodiscitis.” Spondylodiscitis often affects children between the ages of 2 and 8 years and commonly involves the lumbar or lumbosacral spine. Radiographs are usually normal in the early stages of the disease. Spine MRI has a high sensitivity and specificity in early detection of pyogenic infections of the vertebral body and intervertebral discs, paraspinal and epidural abscesses, and myelitis, spinal cord abscess and complications of meningitis. Intravenously administered gadolinium-based contrast agent increases the conspicuity of inflammatory changes in the vertebral bodies and disc and is useful for identifying epidural and paraspinal abscesses [10,11]. Diffusion weighted images (DWI) may help differentiate Modic type 1 degenerative marrow changes from spondylodiscitis and may assist with differentiating epidural abscesses from simple epidural fluid collections [12].

IV. APPLICATIONS OF MRI

D. Vascular Disorders

There are two general categories of vascular spine disorders: spinal cord ischemia (SCI) and vascular malformations.

Abrupt myelopathic signs should raise concern for SCI. Children, however, can have a more prolonged clinical presentation, which often results in delayed diagnosis. MRI is the most sensitive method of detecting the presence of cord ischemia and infarction. Pediatric SCI can be caused by systemic hypotension in the setting of placental abruption, neonatal hypoxic ischemic injury, congenital heart disease, and iatrogenic factors, such as complications from umbilical artery disc catheterization and during surgical instrumentation for scoliosis correction. Fibrocartilaginous embolism (FCE) is a specific cause of pediatric SCI caused by intervertebral annular fissures resulting in extrusion of nucleus pulposus material and reflux of fibrocartilaginous emboli into the arterial

supply of the spinal cord [13-15]. The classic finding of cord infarct on MRI is hyperintense signal acutely involving the anterior two-thirds of the cord ("snake eyes" on axial T2-weighted image) in the vascular distribution of the anterior spinal artery (ASA) [16]. This appearance, however, is nonspecific and can mimic myelopathy of other etiologies, such as infectious myelitis [17]. Unfortunately, over 50% of cases of pediatric SCIs have no identifiable cause.

Vascular malformations that can affect the spinal cord in children include arteriovenous malformations (AVMs), arteriovenous fistulas (AVFs), and cavernous malformations, with AVMs more commonly encountered in children than AVFs [16]. In children, AVMs can be classified into compact (glomus) or diffuse (juvenile) forms [18]. Congenital disorders such as hereditary hemorrhagic telangiectasia, neurofibromatosis type 1, Klippel-Trenaunay-Weber syndrome, and Cobb syndrome are associated with an increased incidence of spinal vascular malformations. MRI is the most sensitive noninvasive method of assessing the spine for vascular malformations, more sensitive in high-flow malformations. MR findings that can indicate the presence of a vascular malformation include visualization of serpentine signal voids in AVMs and posteriorly draining enlarged veins in dural AVFs [19]. MRI is also essential for evaluating the extent of associated cord edema. MRA, with or without contrast administration, can be helpful in depicting pial fistulas and dural AVFs and can be useful in guiding subsequent spinal angiography. Additionally, the utility of high-resolution T2-weighted imaging (eg, T2 SPACE/CUBE/VISTA/amongst others) has also been described to help identify fistula sites and feeding vessels [20]. Spinal cord cavernous malformations typically present in adolescence and are clinically more aggressive than their brain counterparts, although virtually no surrounding edema is present unless there has been recent bleeding in most cases [21]. Identification of a spinal cord cavernous malformation warrants evaluation of the entire central nervous system (CNS) for multiple lesions.

IV. APPLICATIONS OF MRI

E. Trauma

MRI provides excellent visualization of the spinal cord, discs, ligaments, and vessels. Hence it is the preferred imaging modality in pediatric patients presenting with radiographic or CT findings of spinal injury to further evaluate the extent of injury, children with posttraumatic neurologic symptoms and normal or equivocal radiographic or CT findings, and children who are sedated or obtunded, limiting the neurological assessment [22,23]. Additionally, young patients are predisposed to soft-tissue, ligamentous, and cartilaginous injury, particularly at the craniocervical junction, which may be equivocal or occult on CT and radiographs. T1- and T2-weighted, gradient-echo T2* (T2-weighted gradient echo (GRE)*) and fluid sensitive (eg,T2-weighted imaging with fat saturation, short tau inversion recovery (STIR), or T2 Dixon) MRI pulse sequences are preferred in patients with spinal trauma. Many findings related to trauma are readily assessed in the sagittal plane. Axial imaging is helpful in further characterizing injuries, assessing the paraspinal soft tissues for injury, and identifying unexpected vascular injury, such as arterial dissection. Dedicated MR angiography (MRA) of the neck may be indicated if there is a concern for arterial injury on the basis of spinal fracture location (eg, transverse foramen), vertebral body subluxation, signal abnormalities of the arteries, unexplained brain infarct, and direct trauma. High-resolution steady state T2-weighted imaging is useful to evaluate for nerve root avulsion [24]. MRI is usually recommended between 24 and 72 hours or sooner , especially if cord injury or emergent operative intervention is a consideration [25]; however, there is no evidence supporting a more precise guideline. The extent of cord edema has been shown to increase one vertebral level for each 1.2-day delay [26,27]. Spinal subdural hematoma and ligamentous injuries are more commonly associated with abusive head trauma than with accidental head trauma, which increases the specificity of the diagnosis [28]. Abusive head trauma has a high association with ligamentous cervical spine injury [29]. Although prior evidence supported the use of cervical spine MRI in children with suspected abusive head trauma, more recent data demonstrated the presence of thoracolumbar injuries, and therefore evaluation of the entire spine is recommended in cases of suspected abuse [30-32]. Screening protocols of sagittal T2-weighted sequences with fat saturation are often used in abusive head trauma evaluation.

IV. APPLICATIONS OF MRI

F. Neoplasms and neoplastic-like abnormalities

MRI is the preferred and most frequently used modality to evaluate tumors of the spine in the pediatric

population. Superior contrast resolution and multiplanar capabilities allow delineation of the tumor, including, most importantly, the extent of intraspinal involvement. MRI is able to localize the tumor as epidural, intradural-extramedullary, or intramedullary, thus limiting the differential diagnosis. Limited CT may be a useful adjunct modality for assessing bone involvement and evaluating for aggressive margins, the matrix characteristics, and possible sequestrum [33-35]. The administration of gadolinium-based contrast agents further improves sensitivity for lesion detection, improves conspicuity of lesions, and distinguishes solid-enhancing components from cysts or syrinx [35]. The long segment expansile heterogeneously enhancing lesions of many noninfectious inflammatory processes can overlap in appearance with intramedullary spinal cord neoplasms. Prolonged symptom onset is more common in intramedullary spinal cord neoplasms than nonneoplastic entities. The presence of cystic or hemorrhagic changes within an intramedullary lesion or a focal scoliotic curvature at the level of lesion favors a neoplastic etiology [36]. In children, spinal cord neoplasms are most commonly astrocytomas and may have cystic or hemorrhagic changes. Intramedullary spinal ependymomas are rare in children outside the setting of neurofibromatosis type II. Cord diffusion-tensor imaging may be an adjunct technique to determine resectability of a tumor. DWI and dynamic contrast-enhanced T1-weighted perfusion of the spine have also been described as methods to characterize tumors [37].

The presence of drop metastasis or leptomeningeal spread of tumor can be evaluated using an abbreviated protocol, which includes postgadolinium T1-weighted images in both sagittal and axial planes [38,39]. High-resolution, heavily T2-weighted images, such as balanced steady state free precession (bSSFP), have demonstrated improved detection of small drop metastasis [40]. DWI can also be useful as an adjunct to evaluate for CSF tumor dissemination in hypercellular tumors [41,42]. Standardized protocols have been proposed by the Response Assessment in Pediatric Neuro-Oncology (RAPNO) working group as well as in a ACOG Diagnostic Imaging Committee/SPR Oncology Committee/ASPNR White Paper [38,39].

Metastatic osseous neoplasms are less common in the pediatric population, and screening is performed using a number of modalities that include skeletal survey, bone scintigraphy with single-photon emission CT (SPECT), 18F-FDG PET, I123-MIBG scintigraphy, and whole-body MRI [43,44]. However, when spinal involvement is suspected, MRI is the preferred modality to assess for epidural and soft-tissue invasion and associated compression of the spinal cord [33]. In young children, diffuse marrow infiltration by tumor may be more difficult to assess as the marrow signal is not normally diffusely hyperintense on T1-weighted images because of the residual hematopoietic marrow [45,46]. Osteoid osteomas of the spine demonstrate florid bone marrow and soft-tissue edema, which is better depicted on MRI than on CT. Postcontrast imaging with fat-saturation technique is helpful in detecting the nidus [47]. However, these findings are not specific to osteoid osteomas, and MRI features can resemble other entities, such as osteomyelitis, aggressive tumors, acute and subacute fractures, and hyperostosis secondary to mechanical stress reaction [70].

IV. APPLICATIONS OF MRI

G. Miscellaneous

1. Spinal abnormalities associated with scoliosis

   There are three general categories of scoliosis: congenital, neuromuscular, and idiopathic. The imaging modality of choice in the diagnosis, assessment, and surveillance of scoliosis is radiography. CT is used to better understand complex osseous deformities and aids in presurgical planning. MRI is the optimal imaging modality to detect and characterize intraspinal abnormalities that can cause scoliosis, such as tumors, syringomyelia, spinal dysraphisms, and Chiari malformations. MRI is indicated in children with congenital scoliosis and may detect spinal cord abnormalities in approximately 40% of cases [48]. Indications for MRI in patients with neuromuscular scoliosis will vary based on the underlying medical condition and the clinical presentation. MRI is advised in children with scoliosis and concerning clinical manifestations or atypical spinal curves. Imaging sequences typically include sagittal T1- and T2-weighted sequences and axial imaging, although shorter protocols have reported similar accuracy [49]. Coronal imaging is useful in defining abnormalities of vertebral segmentation and formation and in assessing the spinal curve, which is typically less pronounced than on standing radiographs. Fat suppression techniques may confirm congenital fatty lesions. Painful scoliosis evaluation may benefit from fat suppressed T2 or STIR imaging to evaluate for

osseous pathology. Contrast is generally not indicated unless there is concern for a spinal mass.

2. Syringomyelia

   MRI is the examination of choice in diagnosing syringomyelia. MRI can clearly depict the size, location, and extent of syringomyelia and can readily identify congenital and acquired conditions that may cause syringomyelia, such as Chiari deformities and malformations, cervical stenosis, spinal dysraphisms, tumor, arachnoid webs, prior trauma, prior hemorrhage, and infectious or inflammatory conditions. Often, syringomyelia cavities are idiopathic. Sagittal T1- and T2-weighted sequences and axial imaging are typically indicated. T1-weighted imaging facilitates the detection of fatty fila, dermoid cysts, and dermal sinus tracts. Axial T2-weighted imaging aids in accurately identifying the position of the conus, thickened fila, small syringomyelia cavities, dermal sinus tracts, and spinal cord and paraspinal pathology. Heavily T2-weighted sequence, such as 3-D constructive interference in steady state (CISS) or fast imaging employing steady-state acquisition (FIESTA) are helpful in assessing the internal structure of a syringomyelic cavity, identifying subarachnoid webs, and aiding in distinguishing signal loss within the subarachnoid space arising from pulsatile or brisk CSF flow and abnormal vasculature [50]. Septations within a syringomyelia cavity are associated with benignity [51]. Contrast-enhanced imaging is indicated if tumor is suspected. Although studies have suggested that contrast may not always be necessary in the evaluation of an isolated syrinx, further research is needed [52]. Advanced imaging techniques, such as phase-contrast cine flow MRI, may be used to analyze CSF flow dynamics and further insights into syringomyelia formation [53].

3. Postoperative fluid collections and soft-tissue changes

   MRI is well suited to identify postoperative seromas, hematomas, CSF leaks, and pseudomeningoceles.. MRI can clearly depict the relationship between intraspinal and paraspinal postsurgical fluid collections and the spinal cord and nerve roots of the cauda equina. Sagittal T1-weighted and T2-weighted sequences with fat-saturation technique and axial imaging are typically indicated in detecting postoperative fluid collections. Postcontrast imaging is helpful in assessing arachnoiditis and neuritis. CISS or FIESTA sequences may define the location and integrity of the dura, demonstrate the margins of pseudomeningoceles, postoperative fluid collections and CSF leaks, and show internal septations within fluid collections. Postcontrast T1-weighted images with fat saturation and DWI may assist in differentiating sterile postoperative fluid collections from infected ones [54].

4. Spondylolysis

   CT is considered the gold standard in diagnosing spondylolysis. However, CT also exposes the patient to ionizing radiation. Bone scintigraphy involves radiation and is hampered by sensitivity and specificity considerations, often requiring additional evaluation with CT or MRI to confirm the diagnosis of spondylolysis. Standard MRI sequences approach the sensitivity of CT in diagnosing spondylolysis [55]. Sagittal T1-weighted imaging, T2-weighted sequences with fat saturation, and axial imaging are typically indicated in detecting pars interarticularis fractures and marrow edema associated with stress reaction. The sagittal slice thickness should be thin enough to allow visualization of the pars (usually 3 mm). Sequences with fat-saturation techniques are important to display marrow edema associated with acute and subacute pars fractures and stress injury. Using a high spatial resolution spoiled 3-D GRE variant T1 or ultrashort echo time technique in the sagittal plane is likely equivalent to CT for diagnosis [56]. MRI provides the added benefit of demonstrating stress injury of the pars interarticularis in patients withoutassociated spondylolisthesis [57]. Spine radiography has a lower sensitivity than both CT and MRI in detecting spondylolysis but is a low radiation dose, low-cost, and widely available initial screening modality option.

Application of this practice parameter should be in accordance with the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [2] and the ACR–SIR Practice Parameter for Minimal and/or Moderate Sedation/Analgesia [61].

V. SPECIFICATIONS OF THE EXAMINATION

The written or electronic request for MRI of the pediatric spine should provide sufficient information to demonstrate the medical necessity of the examination and allow for its proper performance and interpretation.

Documentation that satisfies medical necessity includes 1) signs and symptoms and/or 2) relevant history (including known diagnoses). Additional information regarding the specific reason for the examination or a provisional diagnosis would be helpful and may at times be needed to allow for the proper performance and interpretation of the examination.

The request for the examination must be originated by a physician or other appropriately licensed health care provider. The accompanying clinical information should be provided by a physician or other appropriately licensed health care provider familiar with the patient's clinical problem or question and consistent with the state scope of practice requirements. (ACR Resolution 35, adopted in 2006 – revised in 2016, Resolution 12-b)

The supervising physician must have a complete understanding of the indications, risks, and benefits of the examination as well as alternative imaging procedures. The physician must be familiar with potential hazards associated with MRI, including potential adverse reactions to contrast media (potential hazards might include spinal hardware if recently implanted, especially in the case of neoplasia or significant trauma). The physician should be familiar with relevant ancillary studies that the patient may have undergone. The physician performing MRI interpretation must have a clear understanding and knowledge of the anatomy and pathophysiology relevant to the MRI examination.

The supervising physician must also understand the imaging parameters, including pulse sequences and field of view, and their effect on the appearance of the images, including the potential generation of image artifacts. Standard imaging protocols may be established and optimized on a case-by-case basis when necessary. These protocols should be reviewed and updated periodically.

V. SPECIFICATIONS OF THE EXAMINATION

A. Patient Selection

The physician responsible for the examination should supervise patient selection and preparation and be available in person or by phone for consultation. Patients must be screened and interviewed before the examination to exclude individuals who may be at risk by exposure to the MR environment [62].

Certain indications require administration of intravenous (IV) contrast media. IV contrast enhancement should be performed using appropriate injection protocols and in accordance with the institution's policy on IV contrast utilization. (See the ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media [63]).

Patients experiencing anxiety or claustrophobia may require sedation or additional assistance. Administration of moderate sedation may be needed to achieve a successful examination. If moderate sedation is necessary, refer to the ACR–SIR Practice Parameter for Minimal and/or Moderate Sedation/Analgesia [61]. For pediatric patients, support from child life specialists can be beneficial and may avoid sedation in some cases.

V. SPECIFICATIONS OF THE EXAMINATION

B. Facility Requirements

Appropriate emergency equipment and medications must be immediately available to treat adverse reactions associated with administered medications. The equipment and medications should be monitored for inventory and drug expiration dates on a regular basis. The equipment, medications, and other emergency support must also be appropriate for the range of ages and sizes in the patient population.

V. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

1. General Principles (highlighting pediatric imaging challenges, including the need for sedation)

MRI protocols should be designed to depict structures of clinical interest as clearly as possible, ideally tailored to the specific clinical concern. Standard protocols that are appropriate for patients of different ages who are suspected of having spinal pathology should be created and implemented.

urface coil receivers are often used, commonly in a phased-array configuration.

Contrast

In addition to imaging based on the intrinsic MR properties of the spinal and paraspinal tissues, some images may be acquired after the IV administration of a paramagnetic MR contrast agent (eg, a chelate of gadolinium). Gadolinium should only be used in appropriate indications, as there is a potential for accumulation of the substance throughout the body, including the brain. Macrocyclic agents may not accumulate within the brain as much as other agents and should be preferentially used when IV contrast is indicated [64]. The clinical importance of gadolinium retention in humans is unknown, but contrast should never be withheld for this reason alone when it is clinically important for MRI diagnosis.

Artifacts

Imaging sequences should minimize artifacts as much as possible. Some of the techniques that are used to move/reduce artifacts include changing the phase and frequency encoding directions (to move pulsation artifact); increasing resolution (to reduce frequency misregistration); applying saturation bands, flow sensitization (for CSF or blood), or respiratory compensation; and altering patient/coil position to improve comfort. Saturation bands, or spatial saturation zones, can be applied outside of the spinal region of interest to suppress signal from these regions so that motion outside the intended field of view (eg, breathing, blood flow, bowel motion) produces less conspicuous artifact in the areas of clinical interest. Physiologic motion suppression techniques and software may help reduce artifacts from patient motion. When dealing with imaging around metal, such as fixation devices, STIR for fat suppression, high-receiver bandwidth, fat-water separation, or multispectral methods for metal artifact suppression may be helpful to reduce artifacts. Specialized metal reduction sequences are now available, depending on the software and hardware being used.

Unsedated pediatric examinations should have their sequence order prioritized to maximize diagnostic information, because scan time may be limited by patient cooperativeness. Children undergoing MR evaluation of the spine sometimes require sedation or anesthesia depending on age and developmental status. Recently, the Food and Drug Administration (FDA) has placed warning labels on general anesthetic and sedation drugs because of concerns over the repeated use in young children. Recent retrospective reviews have not found any sequelae from brief exposures to anesthetic agents [65,66]. Nevertheless, techniques should be considered that increase the success of a unsedated study, such as the involvement of child life, simulation techniques, preparation storybooks, and presenting audio/visual material during the study [67]. In neonates, feed and wrap or bundling techniques may be employed to reduce the need for anesthesia [68].

V. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

2. Pulse Sequences

The choice of MR pulse sequences is generally standardized for most protocols but can be modified by the clinical history and/or physical examination. Commonly used sequences in MRI of the spine include T1; intermediate TE or proton density; T2-weighted sequences; T2*; and various fat suppression techniques. These techniques can be employed as 2-D or 3-D acquisitions. Vascular techniques can be used for MR angiography.

The types of fat suppression include frequency select fat saturation, STIR, and chemical shift techniques (Dixon) [78]. Although these techniques are not all T2-weighted, they can substitute for the T2-weighted sequences noted below. For the purpose of comparison or subtraction, images with fat suppression are sometimes acquired both before and after administration of a contrast agent.

T2* or gradient-echo images have good signal and contrast and are sensitive to local magnetic field heterogeneity (eg, greater signal loss at interfaces between bone and CSF or between bone and soft tissue) and are less sensitive to CSF flow–induced artifacts (eg, signal voids from brisk or pulsatile CSF flow). This technique can be very useful in children as they commonly demonstrate accentuated CSF pulsatility. This sequence is also useful in evaluating for hemorrhage within the cord but has limited use in defining other intramedullary pathology.

T2-weighted steady-state free precession sequences also reduce CSF pulsation artifact and may be useful in evaluating for pathology in the CSF or along the surface of the cord and cauda equina. This sequence is helpful in evaluation of congenital abnormalities and leptomeningeal metastasis, although it is limited in the evaluation of intramedullary pathology [41].

DWI sequences using read-out segmentation may be of additional help in evaluating spinal pathology in children. Evaluation of intra- and extramedullary disease may be improved with improved visualization and characterization [42].

In the cervical spine, wherein the neural foramina are small, T2 volume acquisition with reformations may improve the detection and characterization of neural foraminal pathology. In both congenital and acquired conditions, CT provides additional information about bony abnormalities that may narrow the neural foramina or compromise the spinal canal.

The addition of coronal imaging may be useful in evaluating scoliosis to elucidate associated vertebral anomalies. A sagittal STIR sequence may also be more sensitive to cord pathology as compared with routine T2-weighted images [69].

Axial T1-weighted sequences are sometimes performed, especially for detection of fat in the filum terminale or after IV contrast administration for neoplastic, infections, or inflammatory involvement. Volumetric interpolated GRE sequences may replace routine spin-echo T1 sequences, and although faster, may miss small fatty intrathecal lesions [70]. When evaluating spinal bone marrow for tumor, sagittal T1-weighted sequences should be performed. Fat- suppressed T2-weighted sequences can make focal lesions more conspicuous. When evaluating soft-tissue neoplasms, infections, trauma, muscles, and equivocal cord signal, an axial fluid–sensitive sequence may be helpful. For neoplasms, a contrast-enhanced study may be helpful to further define extraosseous or intramedullary extension of a neoplastic process.

V. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

3. Slice thickness and coil selection

The following are recommended slice thicknesses/gaps for performing the typical spine examinations:

Sequence	Slice thickness	Gap
Sagittal	=3mm	=1mm
Axial	=4mm	=1mm

When attempting to diagnose particular pathologies or in smaller patients, thinner slices may be appropriate. For example, when evaluating for a pars defect, sections that are 3 mm or less in the sagittal plane may be warranted. When attempting to detect and characterize spinal cord pathology, 2-mm sections may be appropriate. Interslice gaps will depend on hardware and software. Avoiding interleave slice order with slice gap (=10%) reduces CSF pulsation artifact on 2-D sequences. Attempts should be made, however, to keep no or minimum interslice gap for

better characterization of smaller leptomeningeal metastases, if the scanner allows without artifact [39]. Contiguous imaging has the advantage of not missing any anatomy. Evaluation of voxel size may be of further guidance with variation according to patient size. Voxel size ranges from 0.6–0.9 mm are recommended. Certain 3-D techniques can also negate CSF pulsation artifacts and reduce or eliminate the slice gap, with improved detection of small leptomeningeal deposits, although with decreased sensitivity for intramedullary T2 changes [40].

V. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

4. Area of coverage

The imaging protocol should be designed to cover the area of clinical interest. Technologists may further evaluate areas of pathology identified on scans while they are being performed. It is recommended that a physician's request be obtained if the scope of the additional area imaged by technologist discretion includes a completely separate body region.

For routine imaging, for example, pain, trauma, weakness, or suspected congenital abnormalities:

Cervical spine: Sagittal and axial images should include from the atlanto-occipital joints through at least the C7 to T1 intervertebral disc. Sagittal imaging should include the entire cervical spine, including parasagittal imaging through all of the neural foramina on both sides. Coronal imaging, if performed, should include the proximal brachial plexus.

Thoracic spine: Sagittal and axial images should include the area of clinical interest. If the entire thoracic spine is to be studied, C7 to L1 should be imaged in the sagittal plane, with axial images obtained as warranted. If no area of interest is identified, axial images should span the entire thoracic spine. In patients whose spines are curved, this may necessitate several axial sequences or reformatted images at different angles. For optimal imaging of the thoracic spinal cord on axial images, the plane of imaging should be as close as possible to perpendicular to the spinal cord (this may require a few sequences in patients with significant thoracic kyphosis). Coronal images may be helpful in cases of severe scoliosis. Sagittal imaging should include the entire thoracic spine, including parasagittal imaging through all of the neural foramina on both sides. Coronal imaging, if performed, should include the exiting nerves in the area of concern, as well as the proximal ribs. Visualization of the craniocervical junction or first rib is useful for accurate localization of thoracic levels and pathology. The upper cervical spine can be obtained on a separate low-resolution sagittal sequence to facilitate accurate counting.

Lumbar spine: The entire lumbar spine should be imaged in the sagittal sequences and include the entire neural foramina and immediate paraspinal soft tissue (T12 to S1). Contiguous axial images (not just through the disc) should be obtained through all levels. If 2-D or nonisotropic voxels are used, dedicated axial images parallel to the discs can be obtained as needed. Coronal imaging should be tailored to the pathology, often to include the exiting nerves at the lower lumbar levels. Imaging should provide enough anatomic coverage to detect transitional anatomy at the lumbosacral junction. Tailored examinations may be appropriate for follow-up of known pathology. Imaging should permit counting of spinal levels, especially in cord tethering, and, if necessary, a low-resolution survey of the entire spine for counting purposes is useful.

For tumor and infection, sagittal and axial images should include the area of clinical interest, and fat suppression on the T2-weighted imaged and postcontrast images may be helpful. If other imaging modalities (or the clinical evaluation) narrows the location of suspected abnormalities, then at times it may be appropriate to limit MRI to these areas of interest. If MRI is to be used as the only diagnostic imaging modality for clinically occult disease, screening of the entire spine may be indicated. For evaluation of intramedullary neoplasms and certain demyelinating conditions, imaging the entire neuraxis may be indicated.

Screening (entire spine): In the pediatric patient, imaging may commonly involve screening the entire spine as clinically indicated. Evaluation for leptomeningeal metastasis as well as congenital anomalies (scoliosis) commonly requires imaging of the entire spine in the sagittal plane. Imaging the whole spine may also be useful to determine

the level of pathology, because children may present with nonlocalizing symptoms and neurologic findings, or the position of the conus. Using multiple-channel spine coils permits coverage of the entire spinal column in fewer imaging sequence sets than separate cervical, thoracic, and lumbar spine imaging, saving time and reducing motion artifact [71].

V. SPECIFICATIONS OF THE EXAMINATION

D. Special Techniques

1. Parallel imaging (PI) – PI shortens the image acquisition time by using the spatial sensitivity information from phased-array RF coils to reduce the number of phase-encoding steps. Multiple-image reconstruction algorithms are available, including space domain–based techniques (SENSE), k-space regenerative techniques (SENSE, SMASH, generalized SMASH, and GRAPPA), and other hybrid techniques [72,73]. The maximum reduction in imaging time, reflected in parallel imaging acceleration factor, is 2–3 in each phase-encoding direction. A potential limitation of using PI is the reduction in signal-to-noise ratio (SNR), which can be compensated by the increased SNR at higher fields, improved surface coils, and advanced acquisition techniques. PI is applicable to all pulse sequences and complementary to other existing acceleration methods. In spine imaging, pulse sequences with high contrast and spatial resolution can be combined with PI and allow evaluation of disc pathology, cord and nerve root impingement, and neural foraminal patency [74-76].

2. Cine imaging for CSF flow – CSF flow can be imaged with phase-contrast cine MRI evaluation. CSF flow imaging is most commonly performed at the level of the foramen magnum in cases of known or suspected Chiari type I or idiopathic syringohydromyelia. It is important to note that in the first 6 –12 months of life, there are reduced CSF pulsation velocities that are due to the compliance of unfused cranial sutures. Cardiac gating with either electrocardiogram (ECG) or peripheral leads can be used to reduce cardiac-dependent flow These approaches also permit quantitative velocity and qualitative vector measurements of CSF flow. Typical parameters are as follows: Cardiac gating; flip angle 20°; repetition time and echo time (TR/TE), 20/5 ms; slice thickness, 5 mm; field of view, 180 mm; matrix, 256 × 256; and encoding velocity (venc) of either 5 cm/s or 10 cm/s. Spinal CSF flow imaging is performed in the axial and/or sagittal planes. Sagittal acquisition allows evaluation of flow ventral to the cervicomedullary junction and dorsal to the cerebellar tonsils. Axial imaging can be performed to look for flow circumferential to the cervicomedullary junction, including evaluation of ventrolateral hyperdynamic flow, which is not evident on midsagittal imaging.

3. Dynamic imaging – Dynamic imaging studies are most commonly performed in children with congenital/developmental disorders predisposing to structural instabilities of the spine, most commonly Down syndrome. The cervical spine is the most common location for these abnormalities. Dynamic MRI may offer a more robust imaging of the cervical spine in children with neurological symptoms or those with concern for hypermobility or instability on dynamic plain films. When performed, dynamic MRI of the spine should be performed under clinical guidance. Current imaging data do not support the routine use of dynamic MRI as a screening tool. Dynamic multiview radiography continues to be the initial imaging modality of choice. When interpreting dynamic studies, it is important to recognize the known alterations in spinal canal diameter and neural foraminal size between extremes of flexion and extension. Although flexion/extension radiography is performed in an upright position to simulate physiologic loading, conventional MRI is performed recumbent. Several technical developments can more closely replicate physiologic loading by incorporating gravity and thus direct axial loading to the spinal axis,including upright MRI and compression devices Currently available literature does not support the use of upright MRI systems in children.

4. Diffusion and DTI – Spine DWI can be a useful tool in the evaluation of the spine and spinal cord in children, although technical challenges, such as artifacts from CSF pulsation and susceptibility artifacts, have limited its use [77]. New techniques, such as reduced field of view (FOV) and readout-segmented echo-planar imaging (EPI) have considerably improved the diagnostic quality of spine DWI [78-81]. Typically, lower B values (400-600) are used in the spine compared to the brain. Spine DWI can detect and characterize diseases that may not be apparent on conventional T1- and T2-weighted imaging. Marrow-replacing diseases encountered in childhood, such as metastatic neuroblastoma or leukemia, can demonstrate

diffuse marrow restriction [82].Drop metastasis from primary pediatric brain tumors can be detected effectively with DWI, particularlyhigh cellularity malignant pediatric brain tumors may not enhance avidly [42]. Spine DWI can also be helpful in characterizing fluid collections that can occur in and around the spine, since adiffusion-restricting fluid collection in the clinical setting of infection is characteristic of an abscess. An isolated fluid collection occurring outside of the setting of infection with diffusion restriction is a classic imaging characteristic of a dermoid cyst. Differentiating degenerative changes from infection can be aided by identifying the characteristic "claw sign" that can occur by the diffusion-restricting reparative response that occurs with degenerative changes [12]. DWI is also helpful in the evaluation of spinal cord pathology. An acute spinal cord infarct can demonstrate acute diffusion restriction very early on during symptom onset [83]. DWI can identify areas of active demyelination within the cord [84]. It can also reveal the heterogeneous pathology of cord tumors and bring attention to areas of cellular proliferation that may indicate malignant degeneration. DTI tractography can highlight axonal disruption as seen as loss of fractional anisotropy from areas of white matter tract displacement. DTI can be helpful in differentiating benign from infiltrative high-grade tumors and in differentiating tumor from demyelination [85].

5. Perfusion imaging – *MR perfusion* studies of *spinal* cord lesions are limited. Perfusion weighted imaging (PWI) parameters are considered direct measures of tissue angiogenesis, vascular density, and capillary permeability in spinal cord tumors, thus providing information about microcirculation in these tumors. The most frequently used perfusion MRI techniques are the (1) dynamic susceptibility contrast (DSC, otherwise called T2* imaging), (2) dynamic contrast-enhanced MRI (DCE-MRI), and (3) arterial spin labeling (ASL). DCE-MRI perfusion parameters have shown limited utility in differentiating local tumor recurrence in adult subjects with spinal metastasis undergoing high-dose radiation therapy [86]. Although perfusion MRI is routinely performed for certain intracranial pathologies, including stroke and tumor imaging, use of perfusion MRI is extremely rare in pediatric patients. Currently, substantial literature is not available to support perfusion MRI techniques in pediatric spinal pathologies.

6. Functional MRI (fMRI) – fMRI of the spine is a noninvasive MRI tool that can be applied to the pediatric spinal cord to study neuronal activity and spinal cord function during sensory and/or motor task paradigms [87]. Spinal fMRI is currently an investigative tool used in the research setting and is not yet optimized for clinical care in children. Potential future clinical applications for spine fMRI in the pediatric population may be in the investigation of spinal cord injury, MS, neuropathic pain, transverse myelitis, hydrosyringomyelia, and tethered cord, among others [88-90].

V. SPECIFICATIONS OF THE EXAMINATION

E. Other Techniques

1. T1-FLAIR versus T1 fast spin-echo (FSE) and T1 spin-echo imaging of the spine [73-76,91-94]

   Historically, T1 imaging of the spine was performed with spin-echo technique. HoweverT1 FSE can provide anatomic detail with a relatively shorter acquisition time compared to conventional spin-echo imaging. Even though T1 FSE often suffers from poor image contrast, it can still generate diagnostic image quality while minimizing patient motion.

   T1-FLAIR imaging is another effective way to obtain T1 contrast at a reasonable image acquisition time, thereby minimizing patient motion. When implemented in an optimized fashion, it can achieve good nulling of the CSF signal, with effective T1-weighting and optimized contrast between bone marrow, CSF, and spinal cord. Moreover, it can also potentially reduce artifacts related to surgical hardware. T1-FLAIR becomes even more advantageous at higher field strengths (especially 3T or greater).

   3D gradient-echo MR images, volumetric interpolated breath-hold examination/liver acquisition with volume acceleration (VIBE/LAVA), have decreased the acquisition time and are more motion-resistant than conventional T1 FSE sequences, although they are less sensitive and may miss small fatty intrathecal lesions [70].

2. Chemical shift imaging [95-99]Chemical shift imaging, also known as opposed-phase or in-and-out-of-phase imaging, is a sequence that takes advantage of small differences in precession frequencies of lipid and water protons to determine the presence of intracellular lipid and water within the same imaging voxel. It can therefore aid in distinguishing between marrow-replacing processes and marrow-preserving processes. Specifically, the technique has shown promise in the ability to distinguish pathologic from benign compression fractures, and there are data that support the ability of opposed-phase imaging to differentiate benign vertebral lesions (eg, hemangiomas, degenerative endplate changes) from malignancy. The T1-weighted GRE sequences can be rapidly acquired, with a total scanning time of 5 minutes or less. Chemical shift imaging can also be used as a technique for fat suppression, and with newer techniques, may be acquired potentially at no additional imaging time. The utility in the pediatric population has not specifically been established.

3. Ultrafast echo time (UTE) and zero echo time (ZTE)

   UTE and ZTE techniques have been introduced to reduce the need to perform a multimodal evaluation, with MRI assessing soft tissue and bone marrow, and CT assessing cortical bone. UTE acquires signal at the end of radiofrequency pulses quickly by using a radial center-out k-space sampling, resulting in TEs of less than 100 μs [100]. ZTE allows near-zero TE (as low as 8 μs) by using continuous gradients with very gradual variation, in addition to non-Cartesian image reconstruction [101]. The result is a high-resolution isotropic data set with improved signal of short T2* species and data acquisition that is more efficient relative to UTE [100]. Studies show that ZTE provides comparable diagnostic information to conventional CT, although may yield a lower spatial resolution than conventional CT [102].

VI. DOCUMENTATION

Reporting should be in accordance with the ACR Practice Parameter for Communication of Diagnostic Imaging Findings [103].

VII. EQUIPMENT SPECIFICATIONS

Equipment performance monitoring should be in accordance with the ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging (MRI) Equipment [104].

The MRI equipment specifications and performance must meet all state and federal requirements. The requirements include, but are not limited to, specifications of maximum static magnetic strength, maximum rate of change of magnetic field strength (dB/dt), maximum RF power deposition (specific absorption rate), and maximum acoustic noise levels.

VIII. QUALITY CONTROL AND IMPROVEMENT, SAFETY, INFECTION CONTROL, AND PATIENT EDUCATION

Policies and procedures related to quality, patient education, infection control, and safety should be developed and implemented in accordance with the ACR Policy on Quality Control and Improvement, Safety, Infection Control, and Patient Education appearing under the heading *Position Statement on QC & Improvement, Safety, Infection Control*, *and Patient Education* on the ACR website (https://www.acr.org/Advocacy-and-Economics/ACR-Position-Statements/Quality-Control-and-Improvement).

Specific policies and procedures related to safety should be in place along with documentation that these policies and procedures are updated annually and that they are formulated under the supervision and direction of the supervising MRI physician. Guidelines that deal with potential hazards associated with MRI examinations should be provided to patients as well as to others in the immediate area. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination [62].

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