2019 (Resolution 5)*

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

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.

The ultimate judgment regarding the propriety of any specific procedure or course of action must be made by the practitioner considering all the circumstances presented. Thus, an approach that differs from the guidance in this document, standing alone, does not necessarily imply that the approach was below the standard of care. To the contrary, a conscientious practitioner may responsibly adopt a course of action different from that set forth in this document when, in the reasonable judgment of the practitioner, such course of action is indicated by variables such as the condition of the patient, limitations of available resources, or advances in knowledge or technology after publication of this document. However, a practitioner who employs an approach substantially different from the guidance in this document may consider documenting in the patient record information sufficient to explain the approach taken.

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.

[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 utilized in neonates younger than 6 months (approximately 3 to 4 months) to assess for spinal contents; its utility, however, diminishes significantly afterward because of the lack of an adequate acoustic window [1].

A variety of imaging modalities can provide diagnostic information based on clinical indications. Of all the imaging tools available for evaluation of pediatric spine disorders, MRI is the most sensitive diagnostic test for detecting anatomic abnormalities of the spine and adjacent structures. However, spine MRI should be performed only for a valid medical reason. Interpretation of imaging findings often benefits from the correlation of findings with the patient's clinical history, clinical examination, or physiologic tests. Adherence to the following practice parameter will enhance the probability of detecting such abnormalities.

II. INDICATIONS

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
            - Meningocele 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
    c. Systemic syndromes associated with motor, bowel, or bladder dysfunction
        i. Caudal regression syndrome that involves partial or complete agenesis of the distal spinal column, imperforate anus, genitourinary anomalies, bilateral renal absence or dysplasia, pulmonary hypoplasia, and lower-extremity anomalies
        ii. Other associations such as Currarino triad, vertebral defects, anal atresia, cardiac defects, tracheoesophageal fistula, renal anomalies, and limb abnormalities (ie, VACTERL)
    d. Congenital spinal cord malformation
        i. Ultrasound (US) finding of a low-lying conus, fatty filum, thickened filum terminale, or intraspinal lesion
        ii. Suspicious cutaneous findings or high dermal pit or sinus

2. Inflammatory/autoimmune disorders
    a. Demyelinating disease
        i. Multiple sclerosis (MS)
        ii. Acute disseminated encephalomyelitis (ADEM)
        iii. Acute inflammatory demyelinating polyradiculopathy (Guillain-Barré syndrome)
        iv. Transverse myelitis
    b. Connective tissue disorders (eg, systemic lupus erythematosus)

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

4. Vascular disorders
   a. Spinal vascular malformations
   b. Spinal cord infarction

5. Trauma
   Nature and extent of traumatic injury to spinal cord, vertebral column, ligaments, thecal sac, and paraspinal soft tissues

6. Neoplastic abnormalities
   a. Intramedullary tumors
   b. Intradural-extramedullary masses
   c. Intradural leptomeningeal disease
   d. Extradural soft-tissue and bony neoplasms
   e. Planning for radiation therapy

7. Degenerative conditions
   a. Degenerative disc disease and its sequelae
   b. Spinal canal stenosis, including foramen magnum narrowing

8. Miscellaneous
   a. Spinal abnormalities associated with scoliosis
   b. Syringohydromyelia (multiple etiologies, including Chiari malformations, trauma, etc)
   c. Postoperative fluid collections and soft-tissue changes (extradural and intradural)
   d. Spondylolysis
   e. Osteoid osteoma

III. 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 Guidance Document on MR Safe Practices [4].

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

IV. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

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

V. APPLICATIONS OF MRI

A. Neoplasms

MRI is the preferred and most frequently utilized 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 [5-7]. 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. Specifically, this is helpful for guiding surgical resection of the solid component in intramedullary tumors associated with cysts [7].

Evaluation for the presence of drop metastasis or leptomeningeal spread of tumor is optimally evaluated using MRI with postgadolinium T1-weighted images in both sagittal and axial planes. Recently, steady-state free precession techniques and diffusion weighted imaging (DWI) have been used to evaluate for cerebrospinal fluid (CSF) tumor dissemination [8,9]. 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 computed tomography (SPECT), 18F-FDG PET, MIBG-I123 scintigraphy, and whole-body MRI [10,11]. However, when spinal involvement is suspected, MRI is the preferred modality to assess for soft-tissue invasion and associated compression of the spinal cord [5]. 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 [12,13].

Spinal screening with MRI may be indicated in patients with multiple familial exostoses to look for occult intracanalicular lesions [14].

B. 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, are predisposed to infection. The infectious process can affect the spinal cord; nerve roots and meninges; epidural space, vertebrae, and the discs [15,16]. 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. An intravenously administered gadolinium-based contrast agent may increase the sensitivity of MRI, providing increased conspicuity of inflammatory changes in both the osseous and the disc components of the disease [17].

Diffusion weighted images (DWI) may help differentiate type 1 degenerative marrow changes from spondylodiscitis [18].

MRI also has a higher sensitivity than CT or radiographs in the detection of associated paravertebral soft-tissue inflammation or abscess.

Spinal epidural abscess is rare but represents a clinically significant condition in children that often requires immediate surgical management [19]. MRI is the imaging modality of choice in spinal epidural abscess. Gadolinium-enhanced T1-weighted sequences have the highest specificity in identifying epidural abscess by demonstrating the rim enhancement surrounding the purulent collection. DWI sequences are also useful in differentiating epidural abscesses from simple epidural fluid collections. Contrast-enhanced MRI is also the imaging modality of choice in assessing infectious processes of the spinal cord and nerve roots. MRI is the initial modality of choice in children with clinically suspected infectious processes, including acute (often viral) myelitis, spinal cord abscess, and meningitis.

Postlumbar puncture extradural fluid collections are common and may be symptomatic but should not be mistaken for epidural abscess [20].

C. Trauma

MRI provides inherent superior contrast resolution in visualizing the spinal cord, discs, ligaments, and vessels. Hence it is the preferred imaging modality in pediatric patients presenting with posttraumatic neurologic symptoms and normal or equivocal radiographic or CT findings and children who are sedated or obtunded, limiting the neurological assessment [21,22]. T1- and T2-weighted, gradient-echo T2* (T2-weighted gradient echo (GRE)*) and short tau inversion recovery (STIR)-weighted 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 magnetic resonance 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, and unexplained brain infarct.

MRI is the gold standard in the diagnosis of spinal cord injuries [23]. Cord edema, transection, and hemorrhage and disc injuries can be aptly detected, which aid in management and prognostication of acute traumatic spinal cord injury [24,25].

MRI is usually recommended between 24 to 72 hours or the earliest possible time depending upon the clinical feasibility of the scan, especially if cord injury is a consideration [26]. That being said, there is no evidence supporting a more precise guideline. The length of edema of the cord is proportional to the time of imaging posttrauma as it has been found that the length of edema increases by one vertebral level each 1.2-day delay [23,25].

Occult spine injuries can best be detected with MRI, and these include bone contusions, compression fractures, and cord and ligamentous injuries [27]. STIR technique, which is used to suppress the signal from fat, is valuable in these cases. Several common vertebral developmental variants can be mistaken for fractures or other pathologic conditions, thus MRI plays a pivotal role in the differentiation of these entities. Abusive head trauma has a high association with ligamentous cervical spine injury [28].

DWI of the spinal cord plays an important role in children with Spinal Cord Injury without Radiographic Abnormality (SCIWORA), especially in patients with a normal appearance of the spinal cord on T2-weighted sequences. Shen et al. have demonstrated the clinical utility of DWI and diffusion tensor imaging (DTI) in the evaluation of patients with SCIWORA [29].

D. Congenital spine lesions

Congenital spine and cord lesions include multiple features of dysmorphology in the pediatric population that start during embryonic development.

Congenital spine malformations are divided into open and closed spinal dysraphisms. Open spinal dysraphism demonstrates externally exposed neural elements through an osseous defect, whereas closed spinal dysraphism does not expose the neural elements; instead, cutaneous stigmata predominate the clinical findings and suggest the underlying dysraphism [30]. In addition, motor, bowel and bladder dysfunctions may suggest spinal 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 [30].

Spinal dysraphism requires thorough investigation of the spine and its contents. Identification of other associated anomalies, such as tethering lesions, diastematomyelia, and Chiari malformation, is important [31].

E. Demyelinating and intramedullary diseases

Intramedullary diseases can be difficult to differentiate clinically, and MRI plays a key role in attempting to make an accurate diagnosis. Clinical features that remain important include characteristics of onset (immediate, rapid, or prolonged), sensory level, and results of CSF sampling. These clinical features play an important role in MRI interpretation.

Abrupt onsets (less than 4 hours to maximal deficit) of nontraumatic myelopathic symptoms are 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, neuromyelitis optica (NMO), lupus myelitis, and other etiologies. When the etiology is unclear, a diagnosis of idiopathic transverse myelitis (ITM) can be made [32]. It is important to note that ITM is not necessarily a final diagnosis, and after completion of all testing, a patient may be determined to have a specific cause for their myelopathy (such as the detection of auto-antibodies to the aquaporin-4 water channel confirming a diagnosis of NMO). In young children with NMO, the aquaporin-4 antibodies may not be detected at initial diagnosis but may become positive later; such a patient may initially be diagnosed with ITM but with an eventual diagnosis of NMO. Imaging of the brain is indicated to evaluate for additional and sometimes typical regions of demyelination.

Although noninfectious demyelinating and inflammatory conditions of the spinal cord have a varied appearance, the lesions are most commonly visible as hyperintense on T2W imaging, and areas of active inflammation or demyelination often enhance after gadolinium administration. Therefore, MRI of the brain and total spine without and with contrast is often indicated for a suspected inflammatory or demyelinating intramedullary process or process affecting the nerve roots of the spinal cord. MS tends to have small lesions that are nonexpansile and peripherally located within the spinal cord, whereas ADEM, NMO, and lupus have long segments (≥3 vertebral levels of involvement) of centrally located expansile lesions [33,34].

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 [35]. 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 DTI may be an adjunct technique to determine resectability of a tumor.

F. Vascular Disorders

Vascular disorders involving the spine in children are similar to adults, but the clinical circumstances under which they occur differ. Risk factors that lead to spinal cord infarcts (SCIs) include systemic hypotension, iatrogenic causes, embolism (fibrocartilagenous) [36], trauma, and vascular anomalies [37]. Abrupt myelopathic signs should raise concern for spinal cord ischemia. Children, however, can have a more prolonged clinical presentation, which often results in delayed diagnosis. The symptoms that occur from cord ischemia vary with the region of the involved cord. Back pain is a very common symptom. Unfortunately, over 50% of cases of pediatric SCIs have no identifiable cause.

There are two general categories of vascular spine disorders: spinal cord ischemia and vascular malformations. 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, and congenital heart disease. The poor auto-regulatory mechanism of the neonate is a further confounding factor. SCI in neonates can also be iatrogenic, such as from complications that are due to umbilical artery catheterization. A high catheter tip placement, thrombus formation, injection of hypertonic solutions, and vasospasm can all lead to SCI. In the older child, SCI may occur because of complications during surgical instrumentation for scoliosis correction. More recently in the literature, awareness has arisen around the entity of fibrocartilagenous embolism (FCE) as a cause of pediatric SCI [36,38]. Although this has not been proven in human research, there is evidence in the scientific literature that this pathophysiologic entity occurs. Intervertebral annular disc tears can result in extrusion of the nucleus pulposus and reflux of fibrocartilagenous emboli into the arterial supply of the spinal cord [39]. The clinical and MRI findings correspond to anterior spinal artery (ASA) territory infarcts.

MRI can demonstrate classic findings of cord infarction, with hyperintense signal acutely involving the anterior two-thirds of the cord (“snake eyes” on axial T2-weighted image) in the vascular distribution of the ASA [40]. The appearance, however, is nonspecific and can mimic myelopathy of other etiologies, such as infectious myelitis [41]. DWI and T1-weighted postcontrast sequences may identify an adjacent vertebral body infarct, which in turn supports the diagnosis of cord infarct [42,43].

Vascular malformations that can affect the spinal cord in children include arteriovenous malformations (AVMs), arteriovenous fistulas (AVFs), and cavernous malformations [40]. Unlike in adults, AVMs are more commonly encountered than AVFs. Although AVFs cause cord ischemia secondary to arterial steal from direct arteriovenous shunting, cord injury in the setting of AVMs occurs secondary to chronic hypoxia. In children, AVMs can be classified into compact (glomus) or diffuse (juvenile) forms [44]. There are congenital disorders that are associated with an increased incidence of spine vascular malformations, such as hereditary hemorrhagic telangiectasia, Neurofibromatosis type 1, Klippel-Trenaunay-Weber syndrome, and Cobb syndrome. MR imaging is the most successful noninvasive method of assessing the spine for vascular malformations. MR

findings that can indicate the presence of a vascular malformation include visualization of serpentine signal voids in AVMs or posteriorly draining enlarged veins in dural AVFs [45]. An MR finding that can be misinterpreted for a spinal vascular malformation is CSF flow artifact commonly encountered in the thoracic region of children. Spinal cord cavernous malformations typically present in adolescence and are clinically more aggressive than their brain counterparts [46]. They appear as focal lesions containing byproducts of hemoglobin degradation. In most cases, virtually no surrounding edema is present unless there has been recent bleeding. Identification of a spinal cord cavernous malformation warrants evaluation of the entire central nervous system (CNS) for multiple lesions. MR imaging is also sensitive to secondary changes in the cord, such as venous congestion and gadolinium enhancement. 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.

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 utilized 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 cavities, spinal dysraphisms, and Chiari malformations. MRI is indicated in children with congenital scoliosis and may detect spinal cord abnormalities in approximately 40% of cases [47]. In the youngest of these children, sonography can be helpful to assess for intraspinal pathology as an initial imaging screening option. 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. Indications for MRI in patients with idiopathic scoliosis are not clearly established. MRI is often obtained prior to corrective spine surgery.

Imaging sequences typically include sagittal T1- and T2-weighted sequences and axial imaging. Slice thickness will depend on the area to be imaged. 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 type I malformations, cervical stenosis, spinal dysraphisms, tumor, arachnoid webs, prior trauma, prior hemorrhage, and infectious or inflammatory conditions. Often, syringomyelia cavities are idiopathic. Septations within a syringomyelia cavity are associated with benignity [48]. Contrast-enhanced imaging is indicated if tumor is suspected. However, contrast-enhanced imaging may not be necessary to rule out a syrinx-associated spinal cord mass if diagnostic-quality sagittal and axial T2-weighted images are available for analysis [49]. Advanced imaging techniques, such as phase-contrast cine flow MRI, may be used to analyze CSF flow dynamics and further insights into syringomyelia formation [50].

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 [51].

3. Postoperative fluid collections and soft-tissue changes

MRI is well-suited to identify postoperative seromas, hematomas, CSF leaks, and pseudomeningoceles. MRI has high sensitivity and specificity relative to CT and bone scintigraphy because of the superior soft-tissue contrast inherent to MRI and avoids ionizing radiation [52,53]. MRI can clearly depict the relationship between intraspinal and paraspinal post-surgical 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 superinfected 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]. Utilizing a high spatial resolution spoiled 3-D GRE variant T1 technique in the sagittal plane is likely equivalent to CT for diagnosis. MRI provides the added benefit of demonstrating stress injury of the pars interarticularis in patients without a frank pars fracture [56].

Sagittal T1-weighted imaging, T2-weighted sequences with fat saturation, and axial imaging are typically indicated in detecting pars interarticularis fractures. 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. 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.

5. Osteoid Osteoma

Osteoid osteomas of the spine have a predilection for the posterior elements [57]. CT is superior to MRI in diagnosing and characterizing osteoid osteomas and is used for radiofrequency (RF) ablation. CT readily depicts the characteristic nidus, periosteal reaction and osteosclerosis of osteoid osteomas [58]. Dynamic gadolinium-enhanced MRI may also demonstrate the enhancing nidus with sensitivities approaching that of CT [59]. The florid bone marrow and soft-tissue edema often associated with an osteoid osteoma is better depicted on MRI than on CT. 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 [60]. Radiography has low sensitivity because of overlapping spinal anatomy. Bone scintigraphy is useful in confirming osteoid osteomas in atypical cases [58].

Sagittal T1- and T2-weighted sequences and axial imaging are typically indicated. T2-weighted imaging with fat-saturation technique is important to show marrow and soft-tissue edema. Postcontrast imaging with fat-saturation technique is helpful in detecting the nidus [58].

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 Sedation/Analgesia [61].

VI. WRITTEN REQUEST FOR 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)

VII. SPECIFICATIONS OF THE EXAMINATION

The supervising physician must have 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.

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 prior to the examination to exclude individuals who may be at risk by exposure to the MR environment.

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 [62]).

Patients suffering from 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 Sedation/Analgesia [61].

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.

C. Examination Technique

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

   MRI should depict structures as clearly as possible. Standard protocols that are appropriate for patients of different ages who are suspected of having spinal pathology should be created and implemented. The precise details of that performance may vary among equipment (magnets, coils, and software), patient, and the personal preferences of the radiologists who manage and interpret the studies. Generally, images should cover the relevant anatomy/pathology.

The MR signal that is produced from a region of the spine (cervical, thoracic, and lumbosacral) in response to a particular pulse sequence is often, but not always, detected using surface coil receivers, commonly in a phased-array configuration.

Contrast

In addition to images with contrast based on 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). This agent is used to detect regions in which the normal vascular circulation has been altered by injury or disease. For example, the use of IV paramagnetic contrast is recommended for evaluation of infection and neoplasm. Routine use of gadolinium should be avoided as there is a potential for accumulation of the substance within the brain. Macrocyclic agents may not accumulate within the brain as much as other agents [63]. That being said, at this time, the clinical importance of gadolinium retention in humans is unknown.

Artifacts

Imaging sequences should minimize artifacts as much as possible.

Physicians in conjunction with technologists should determine the pulse sequences to be used. Physicians who interpret spine MR examinations must understand the artifacts associated with and the limitations of the various imaging pulse sequences. They must use techniques to minimize inherent artifacts (such as pulsation artifact) when it is likely to obscure pathology. Some of the techniques that are used to move/reduce artifacts include changing phase and frequency directions (to move pulsation artifact), increase resolution (to reduce frequency misregistration), apply saturation bands, flow sensitization (for CSF or blood), alterations in patient/coil position to improve comfort, and respiratory compensation.

Saturation bands, or spatial saturation zones, can be applied outside of the spinal region of interest. They 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.

Nonsedated pediatric studies should undergo sequence prioritization as 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) 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 [64,65]. However, techniques should be employed to increase the success of a nonsedated study, such as involvement of child life, simulation techniques, a preparation storybook, and the ability to present audio/visual material during the study [66]. In neonates, feed and wrap or bundling techniques may be employed to reduce the need for anesthesia [67].

2. Pulse sequences

The choice of MR pulse sequences is generally standardized for particular studies but can be guided by the clinical history and physical examination. Commonly used sequences in MRI of the spine include T1; intermediate TE, proton density, or fluid-attenuated inversion recovery (FLAIR); 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 angiography. The types of fat suppression include frequency select fat saturation, STIR, and chemical shift techniques (Dixon) [68]. 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 the contrast agent.

T2* or gradient-echo images have a 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 that are due to brisk or pulsatile CSF flow). This technique can be very useful in children as they commonly demonstrate accentuated pulsatility of the CSF. 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 [8].

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 [9].

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.

Minimum recommended pulse sequences for evaluating the spine for pain, radiculopathy, or suspected congenital abnormality may include:

-Sagittal T1 weighted
-Sagittal T2 weighted, STIR, or T2 Dixon
-Axial T2 weighted

Coronal STIR or T2-weighted sequences are very helpful, especially in the lumbar and thoracic spines. Axial T1-weighted sequences are sometimes performed, especially in the lumbar spine, 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.

When evaluating spinal bone marrow for tumor, sagittal T1-weighted sequences should be performed. Fat-suppressed T2-weighted or STIR sequences, as well T2 Dixon techniques, 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.

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

3. Slice thickness and coil selection

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

Sequence	Slice thickness	Gap
Cervical spine - sagittal	3mm	1mm
Cervical spine - axial	4mm	1mm
Thoracic spine - sagittal	3mm	1mm
Thoracic spine - axial	4mm	1mm
Lumbar spine - sagittal	3mm	1mm
Lumbar spine - 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. 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 to 0.9 mm are recommended.

4. Area of coverage

The imaging protocol should be designed to cover the area of clinical interest. Because the clinical situation is a crucial determinant of treatment, the following are general recommendations and not strict criteria. In addition to covering 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 complete 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 unless there is a specific area of clinical concern, in which case that area should be covered.

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.

For thoracic imaging, 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.

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.

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 can 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 narrow the levels 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, it may be reasonable to image the brain as well.

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, as children may present with nonlocalizing symptoms and neurologic findings, or the position of the conus. Utilization of 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 [70].

D. Special techniques

1. Parallel imaging

A potential limitation of MRI in the spine is the relatively longer acquisition time in nonsedated children. Lengthy scan times could result in increased motion-related artifacts and raise the number of sedated MRI studies. Parallel imaging is a technological innovation that allows accelerated MRI data acquisition that could substantially reduce the scan duration. Parallel imaging (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 (SMASH, generalized SMASH, and GRAPPA), and other hybrid techniques [71,72]. Although many parallel imaging techniques exist, these can be broadly classified into two separate groups: (a) methods that work with aliased images and (b) methods that reconstruct missing k-space data. The maximum reduction in imaging time, reflected in parallel imaging acceleration factor, is 2 to 3 in each phase-encoding direction. A potential limitation of using parallel imaging 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. Parallel imaging 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 [73-75].

In the cervical spine, parallel imaging has been shown to reduce scan time by up to 50% of normal while preserving adequate image quality [76].

2. Cine imaging for CSF flow

CSF flow can be imaged with phase-contrast cine MRI evaluation. Cardiac gating with either electrocardiogram (ECG) or peripheral leads can be used to reduce cardiac-dependent flow artifacts. 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.

This is most commonly performed at the level of the foramen magnum in cases of known or suspected Chiari type I malformation or idiopathic syringohydromyelia. It is important to note that in the first 6 to 12 months of life, there are reduced CSF pulsation velocities that are due to the compliance of unfused cranial sutures.

3. Dynamic imaging

Dynamic MRI of the spine attempts to reproduce the relative position of various spinal elements during physiological loading or by imaging the spine in various anatomic positions. The conventional and most common form of dynamic imaging of the spine that may be employed in children consists of the flexion and extension images. Dynamic imaging studies are often performed in children with congenital/developmental disorders predisposing to structural instabilities of the spine, most commonly employed in patients with Down syndrome. The cervical spine is the most common location for these abnormalities. Dynamic MRI could 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.

Capabilities to study the spine under physiologic load are limited on most conventional scanners. Although flexion/extension radiography is performed in an upright position to simulate physiologic loading, conventional MRI is performed recumbent. This deficiency has led to several technical developments in adults that more closely replicate physiologic loading by incorporating gravity and thus direct axial loading to the spinal axis. This includes upright MRI and compression devices that can provide an equivalent axial load to the spinal axis even while imaging in the supine position.

Upright MRI units in particular are designed to image the spine in a variety of normal physiologic conditions: supine, upright, sitting, flexion, extension, or a combination of postures. Moreover, these devices are designed to demonstrate anatomic changes between modes of positioning. Currently available literature does not support the use of upright MRI systems in children.

4. Diffusion and DTI

Spine DWI has been shown to be a useful tool in the evaluation of the spine and spinal cord in children. Although diffusion imaging comprises a standard sequence in the evaluation of brain pathology, technical challenges have limited its application in the spine. Technical limitations in spine DWI are caused by artifacts from CSF pulsation and susceptibility artifacts that cause image distortion [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].

Spine DWI can detect and characterize disease 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]. The increased amount of red marrow in children’s spines as compared with adults can make it difficult to appreciate the presence of disease without

DWI. Drop metastases from primary pediatric brain tumors is a frequent mode of neoplastic spread of disease in children and can be detected effectively with DWI. High cellularity malignant pediatric brain tumors may not enhance avidly, and therefore spread of disease on T1 postcontrast imaging can be difficult to detect. Spine DWI has been shown to have the ability to detect hypercellular metastases that are not apparent on postcontrast imaging alone [9].

Spine DWI can also be helpful in characterizing fluid collections that can occur in and around the spine. A diffusion-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 [18].

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

In humans, MR perfusion studies of spinal cord lesions are limited to very few related articles, often in the cervical region. 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). All techniques could offer noninvasive details of microvascular structures and hemodynamics, not immediately obtained from traditional MRI techniques. ASL perfusion study is performed without the use of intravenous IV contrast agent. DSC MR perfusion, which is sensitive to transient changes in magnetic susceptibility caused by a contrast bolus, readily offers quantitative measurement, which tracks T1 changes caused by IV contrast, assessing regional perfusion, including regional blood volume, blood flow, and mean transit time. DCE-MRI could provide details above the intravascular volume (Vp) as well as the rate of contrast leakage from the intravascular to interstitial space (K^{trans}). 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

Functional MRI (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 utilized 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].

E. Other Techniques

1. T1-FLAIR versus T1 fast spin-echo (FSE) and T1 spin-echo imaging of the spine [91-94][72-75]

Though traditionally, T1 imaging of the spine has been performed with spin-echo technique, T1 FSE can provide anatomic detail at a relatively short acquisition time compared with 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, 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 the bone marrow, CSF, and spinal cord. Moreover, it can also potentially reduce artifact related to surgical hardware. However, care must be taken at effective implementation to ensure bone marrow contrast and lesion conspicuity. T1-FLAIR becomes even more advantageous at higher field strengths (especially 3T or greater).

2. Chemical shift imaging [95-99][76-80]

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 (hemangiomas, degenerative endplate changes, etc) 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.

VIII. DOCUMENTATION

Reporting should be in accordance with the ACR Practice Parameter for Communication of Diagnostic Imaging Findings [100].

IX. EQUIPMENT SPECIFICATIONS

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.

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 [101].

X. 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 the 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.

ACKNOWLEDGEMENTS

This practice parameter was revised according to the process described under the heading *The Process for Developing ACR Practice Guidelines and Technical Standards* on the ACR website (https://www.acr.org/Clinical-Resources/Practice-Parameters-and-Technical-Standards) by the Committee on Practice Parameters – Pediatric Radiology of the ACR Commission on Pediatric Radiology and the Committee on Practice Parameters – Neuroradiology of the ACR Commission on Neuroradiology, in collaboration with the ASNR and the SPR.

Collaborative Committee – members represent their societies in the initial and final revision of this practice parameter

ACR	ASNR	SPR
Sumit Pruthi, MBBS, Chair	David Joyner, MD	Mariaem M. Andres, MD
Timothy N. Booth, MD	Neel Madan, MD	Nancy Rollins, MD
Asim F. Choudhri, MD	Alexander McKinney, MD	Victoria Michelle Silvera, MD
Susan Palasis, MD		
Unni Udayasanakar, MD		

Committee on Practice Parameters – Pediatric Radiology
(ACR Committee responsible for sponsoring the draft through the process)

Beverley Newman, MB, BCh, BSc, FACR, Chair	Kerri A. Highmore, MD
Timothy J. Carmody, MD, FACR	Sue C. Kaste, DO
Tara M. Catanzano, MB, BCh	Terry L. Levin, MD, FACR
Lee K. Collins, MD	Matthew P. Lungren, MD, MPH
Kassa Darge, MD, PhD	Helen R. Nadel, MD
Monica S. Epelman, MD	Sumit Pruthi, MBBS
Dorothy L. Gilbertson-Dahdal, MD	Pallavi Sagar, MD
Safwan S. Halabi, MD	Richard B. Towbin, MD, FACR

Committee on Practice Parameters – Neuroradiology
(ACR Committee responsible for sponsoring the draft through the process)

Steven W. Hetts, MD, Chair	Robert J. McDonald, MD
Kristine A. Blackham, MD	Alexander M. McKinney, IV, MD
Brian A. Conley, MD	David M. Mirsky, MD
Kavita K. Erickson, MD	Robin J. Mitnick, MD, FACR
Adam E. Flanders, MD	Lubdha M. Shah, MD
H. Simms Hardin, IV, MD	Raymond K. Tu, MD, FACR, Chair
John E. Jordan, MD, MPP, FACR	Max Wintermark, MD
Jacqueline C. Junn, MD	

Alexander M. Norbash, MD, FACR, Chair, Commission on Neuroradiology
Richard A. Barth, MD, FACR, Chair, Commission on Pediatric Radiology
Jacqueline Anne Bello, MD, FACR, Chair, Commission on Quality and Safety
Matthew S. Pollack, MD, FACR, Chair, Committee on Practice Parameters and Technical Standards
Mary S. Newell, MD, FACR, Vice Chair, Committee on Practice Parameters and Technical Standards

Comments Reconciliation Committee

Amy Kotsenas, MD, FACR, Chair	Alexander McKinney, MD
Colin Segovis, MD, PhD, Co-Chair	Douglas N. Mintz, MD, FACR
Mariaem M. Andres, MD	Mary S. Newell, MD, FACR
Richard A. Barth, MD, FACR	Beverley Newman, MB, BCh, BSc, FACR
Jacqueline A. Bello, MD, FACR	Alexander M. Norbash, MD, FACR
Timothy N. Booth, MD	Susan Palasis, MD

Comments Reconciliation Committee

Jeffrey M. Brody, MD, FACR
Asim F. Choudhri, MD
Richard Duszak, Jr., MD, FACR
Steven W. Hetts, MD
David Joyner, MD
Paul A. Larson, MD, FACR
Neel Madan, MD
Matthew S. Pollack, MD, FACR
Sumit Pruthi, MBBS
Nancy Rollins, MD
Michael Ian Rothman, MD, FACR
Victoria Michelle Silvera, MD
Timothy L. Swan, MD, FACR
Unni Udayasanakar, MD

REFERENCES

1. Unsinn KM, Geley T, Freund MC, Gassner I. US of the spinal cord in newborns: spectrum of normal findings, variants, congenital anomalies, and acquired diseases. *Radiographics.* 2000;20(4):923-938.
2. American College of Radiology. ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI). 2017; Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/MR-Perf-Interpret.pdf. Accessed Ocotber 2, 2018.
3. American College of Radiology. ACR Manual on Contrast Media. 2018; Available at: https://www.acr.org/-/media/ACR/Files/Clinical-Resources/Contrast_Media.pdf. Accessed October 2, 2018.
4. Expert Panel on MRS, Kanal E, Barkovich AJ, et al. ACR guidance document on MR safe practices: 2013. *J Magn Reson Imaging.* 2013;37(3):501-530.
5. Menashe SJ, Iyer RS. Pediatric Spinal Neoplasia: A Practical Imaging Overview of Intramedullary, Intradural, and Osseous Tumors. *Current Problems in Diagnostic Radiology.* 2013;42(6):249-265.
6. Huisman TAGM. Pediatric tumors of the spine. *Cancer Imaging.* 2009;9(Special issue A):S45-S48.
7. Palasis S, Hayes LL. Acquired pathology of the pediatric spine and spinal cord. *Pediatr Radiol.* 2015;45 Suppl 3:S420-432.
8. Soares BP, Mabray M, MacKenzie JD, Sun PP, Martin KW. Pediatric Spine Disorders: Appearance on Steady-State Free Precession MR Images. *Neurographics.* 2014;4(3):133-138.
9. Hayes LL, Jones RA, Porter DA, et al. Diffusion-Weighted Imaging of the Pediatric Spine Using Readout-Segmented Echo Planar Imaging: A Pictorial Review of Clinical Applications. *Neurographics.* 2015;5(5):197-208.
10. Daldrup-Link HE, Franzius C, Link TM, et al. Whole-body MR imaging for detection of bone metastases in children and young adults: comparison with skeletal scintigraphy and FDG PET. *AJR Am J Roentgenol.* 2001;177(1):229-236.
11. Algra PR, Bloem JL, Tissing H, Falke TH, Arndt JW, Verboom LJ. Detection of vertebral metastases: comparison between MR imaging and bone scintigraphy. *Radiographics.* 1991;11(2):219-232.
12. Ruzal-Shapiro C, Berdon WE, Cohen MD, Abramson SJ. MR imaging of diffuse bone marrow replacement in pediatric patients with cancer. *Radiology.* 1991;181(2):587-589.
13. Taccone A, Oddone M, Occhi M, Dell'Acqua AD, Ciccone MA. MRI "road-map" of normal age-related bone marrow. I. Cranial bone and spine. *Pediatr Radiol.* 1995;25(8):588-595.
14. Ashraf A, Larson AN, Ferski G, Mielke CH, Wetjen NM, Guidera KJ. Spinal stenosis frequent in children with multiple hereditary exostoses. *J Child Orthop.* 2013;7(3):183-194.
15. Fucs PM, Meves R, Yamada HH. Spinal infections in children: a review. *Int Orthop.* 2012;36(2):387-395.
16. Murphy KJ, Brunberg JA, Quint DJ, Kazanjian PH. Spinal cord infection: myelitis and abscess formation. *AJNR Am J Neuroradiol.* 1998;19(2):341-348.
17. Brown R, Hussain M, McHugh K, Novelli V, Jones D. Discitis in young children. *J Bone Joint Surg Br.* 2001;83(1):106-111.
18. Patel KB, Poplawski MM, Pawha PS, Naidich TP, Tanenbaum LN. Diffusion-weighted MRI "claw sign" improves differentiation of infectious from degenerative modic type 1 signal changes of the spine. *AJNR Am J Neuroradiol.* 2014;35(8):1647-1652.
19. James SL, Davies AM. Imaging of infectious spinal disorders in children and adults. *Eur J Radiol.* 2006;58(1):27-40.
20. Koch BL, Moosbrugger EA, Egelhoff JC. Symptomatic spinal epidural collections after lumbar puncture in children. *AJNR Am J Neuroradiol.* 2007;28(9):1811-1816.
21. Booth TN. Cervical spine evaluation in pediatric trauma. *AJR Am J Roentgenol.* 2012;198(5):W417-425.

22. Frank JB, Lim CK, Flynn JM, Dormans JP. The efficacy of magnetic resonance imaging in pediatric cervical spine clearance. *Spine (Phila Pa 1976).* 2002;27(11):1176-1179.
23. Pizones J, Izquierdo E, Alvarez P, et al. Impact of magnetic resonance imaging on decision making for thoracolumbar traumatic fracture diagnosis and treatment. *Eur Spine J.* 2011;20 Suppl 3:390-396.
24. Bozzo A, Marcoux J, Radhakrishna M, Pelletier J, Goulet B. The role of magnetic resonance imaging in the management of acute spinal cord injury. *J Neurotrauma.* 2011;28(8):1401-1411.
25. Lubicky JP, Gussous YM. Thoracolumbar Spine Injuries in Children and Adolescents. *Seminars in Spine Surgery.* 2010;22(1):44-49.
26. Bondurant FJ, Cotler HB, Kulkarni MV, McArdle CB, Harris JH, Jr. Acute spinal cord injury. A study using physical examination and magnetic resonance imaging. *Spine (Phila Pa 1976).* 1990;15(3):161-168.
27. Gamanagatti S, Rathinam D, Rangarajan K, Kumar A, Farooque K, Sharma V. Imaging evaluation of traumatic thoracolumbar spine injuries: Radiological review. *World J Radiol.* 2015;7(9):253-265.
28. Jacob R, Cox M, Koral K, et al. MR Imaging of the Cervical Spine in Nonaccidental Trauma: A Tertiary Institution Experience. *AJNR Am J Neuroradiol.* 2016.
29. Shen H, Tang Y, Huang L, et al. Applications of diffusion-weighted MRI in thoracic spinal cord injury without radiographic abnormality. *Int Orthop.* 2007;31(3):375-383.
30. Schwartz ES, Rossi A. Congenital spine anomalies: the closed spinal dysraphisms. *Pediatr Radiol.* 2015;45 Suppl 3:S413-419.
31. Valeur NS, Iyer RS, Ishak GE. Cervicothoracic cystic dysraphism. *Pediatr Radiol.* 2016;46(10):1471-1481.
32. Transverse Myelitis Consortium Working G. Proposed diagnostic criteria and nosology of acute transverse myelitis. *Neurology.* 2002;59(4):499-505.
33. Lalan S, Khan M, Schlakman B, Penman A, Gatlin J, Herndon R. Differentiation of neuromyelitis optica from multiple sclerosis on spinal magnetic resonance imaging. *Int J MS Care.* 2012;14(4):209-214.
34. Wolf VL, Lupo PJ, Lotze TE. Pediatric acute transverse myelitis overview and differential diagnosis. *J Child Neurol.* 2012;27(11):1426-1436.
35. Barkovich AJ. Intramedullary Space. *Diagnostic Imaging: Pediatric Neuroradiology, 2nd Edition,*: Elsevier; 2014:1-30.
36. Nance JR, Golomb MR. Ischemic spinal cord infarction in children without vertebral fracture. *Pediatr Neurol.* 2007;36(4):209-216.
37. Spencer SP, Brock TD, Matthews RR, Stevens WK. Three unique presentations of atraumatic spinal cord infarction in the pediatric emergency department. *Pediatr Emerg Care.* 2014;30(5):354-357.
38. Stettler S, El-Koussy M, Ritter B, et al. Non-traumatic spinal cord ischaemia in childhood - clinical manifestation, neuroimaging and outcome. *Eur J Paediatr Neurol.* 2013;17(2):176-184.
39. AbdelRazek MA, Mowla A, Farooq S, Silvestri N, Sawyer R, Wolfe G. Fibrocartilaginous embolism: a comprehensive review of an under-studied cause of spinal cord infarction and proposed diagnostic criteria. *J Spinal Cord Med.* 2016;39(2):146-154.
40. Krings T, Lasjaunias PL, Hans FJ, et al. Imaging in spinal vascular disease. *Neuroimaging Clin N Am.* 2007;17(1):57-72.
41. Weidauer S, Nichtweiss M, Lanfermann H, Zanella FE. Spinal cord infarction: MR imaging and clinical features in 16 cases. *Neuroradiology.* 2002;44(10):851-857.
42. Diehn FE, Hunt CH, Lehman VT, et al. Vertebral body infarct and ventral cauda equina enhancement: two confirmatory findings of acute spinal cord infarct. *J Neuroimaging.* 2015;25(1):133-135.
43. Srikanth SG, Chandrashekhar HS, Shankar JJ, Ravishankar S, Shankar SK. Vertebral body signal changes in spinal cord infarction: histopathological confirmation. *Neuroradiol J.* 2007;20(5):580-585.
44. Spetzler RF, Detwiler PW, Riina HA, Porter RW. Modified classification of spinal cord vascular lesions. *J Neurosurg.* 2002;96(2 Suppl):145-156.
45. Song D, Garton HJ, Fahim DK, Maher CO. Spinal cord vascular malformations in children. *Neurosurg Clin N Am.* 2010;21(3):503-510.
46. Noudel R, Litre F, Vinchon M, Patey M, Rousseaux P. Intramedullary spinal cord cavernous angioma in children: case report and literature review. *Childs Nerv Syst.* 2008;24(2):259-263.
47. Arlet V, Odent T, Aebi M. Congenital scoliosis. *Eur Spine J.* 2003;12(5):456-463.
48. Lederhaus SC, Pritz MB, Pribram HF. Septation in syringomyelia and its possible clinical significance. *Neurosurgery.* 1988;22(6 Pt 1):1064-1067.
49. Timpone VM, Patel SH. MRI of a syrinx: is contrast material always necessary? *AJR Am J Roentgenol.* 2015;204(5):1082-1085.

50. Struck AF, Haughton VM. Idiopathic syringomyelia: phase-contrast MR of cerebrospinal fluid flow dynamics at level of foramen magnum. *Radiology.* 2009;253(1):184-190.
51. Roser F, Ebner FH, Danz S, et al. Three-dimensional constructive interference in steady-state magnetic resonance imaging in syringomyelia: advantages over conventional imaging. *J Neurosurg Spine.* 2008;8(5):429-435.
52. Dagirmanjian A, Schils J, McHenry M, Modic MT. MR imaging of vertebral osteomyelitis revisited. *AJR Am J Roentgenol.* 1996;167(6):1539-1543.
53. Hong SH, Choi JY, Lee JW, Kim NR, Choi JA, Kang HS. MR imaging assessment of the spine: infection or an imitation? *Radiographics.* 2009;29(2):599-612.
54. Kumar Y, Khaleel M, Boothe E, Awdeh H, Wadhwa V, Chhabra A. Role of Diffusion Weighted Imaging in Musculoskeletal Infections: Current Perspectives. *Eur Radiol.* 2017;27(1):414-423.
55. Ganiyusufoglu AK, Onat L, Karatoprak O, Enercan M, Hamzaoglu A. Diagnostic accuracy of magnetic resonance imaging versus computed tomography in stress fractures of the lumbar spine. *Clin Radiol.* 2010;65(11):902-907.
56. Ledonio CG, Burton DC, Crawford CH, 3rd, et al. Current Evidence Regarding Diagnostic Imaging Methods for Pediatric Lumbar Spondylolysis: A Report From the Scoliosis Research Society Evidence-Based Medicine Committee. *Spine Deform.* 2017;5(2):97-101.
57. Chai JW, Hong SH, Choi JY, et al. Radiologic diagnosis of osteoid osteoma: from simple to challenging findings. *Radiographics.* 2010;30(3):737-749.
58. Iyer RS, Chapman T, Chew FS. Pediatric bone imaging: diagnostic imaging of osteoid osteoma. *AJR Am J Roentgenol.* 2012;198(5):1039-1052.
59. Liu PT, Chivers FS, Roberts CC, Schultz CJ, Beauchamp CP. Imaging of osteoid osteoma with dynamic gadolinium-enhanced MR imaging. *Radiology.* 2003;227(3):691-700.
60. Davies M, Cassar-Pullicino VN, Davies AM, McCall IW, Tyrrell PN. The diagnostic accuracy of MR imaging in osteoid osteoma. *Skeletal Radiol.* 2002;31(10):559-569.
61. American College of Radiology. ACR-SIR Practice Parameter for Sedation/Analgesia. 2015; Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/Sed-Analgesia.pdf. Accessed October 2, 2018.
62. American College of Radiology. ACR–SPR Practice Parameter for the use of Intravascular Contrast Media. 2017; Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/IVCM.pdf. Accessed October 2, 2018.
63. Radbruch A, Haase R, Kickingereder P, et al. Pediatric Brain: No Increased Signal Intensity in the Dentate Nucleus on Unenhanced T1-weighted MR Images after Consecutive Exposure to a Macrocyclic Gadolinium-based Contrast Agent. *Radiology.* 2017;283(3):828-836.
64. Davidson AJ, Disma N, de Graaff JC, et al. Neurodevelopmental outcome at 2 years of age after general anaesthesia and awake-regional anaesthesia in infancy (GAS): an international multicentre, randomised controlled trial. *Lancet.* 2016;387(10015):239-250.
65. Sun LS, Li G, Miller TLK, et al. Association Between a Single General Anesthesia Exposure Before Age 36 Months and Neurocognitive Outcomes in Later Childhood. *JAMA.* 2016;315(21):2312-2320.
66. Tornqvist E, Mansson A, Hallstrom I. Children having magnetic resonance imaging: A preparatory storybook and audio/visual media are preferable to anesthesia or deep sedation. *J Child Health Care.* 2015;19(3):359-369.
67. Antonov NK, Ruzal-Shapiro CB, Morel KD, et al. Feed and Wrap MRI Technique in Infants. *Clin Pediatr (Phila).* 2016.
68. Pokorney AL, Chia JM, Pfeifer CM, Miller JH, Hu HH. Improved fat-suppression homogeneity with mDIXON turbo spin echo (TSE) in pediatric spine imaging at 3.0 T. *Acta Radiol.* 2017:284185117690424.
69. Alcaide-Leon P, Pauranik A, Alshafai L, et al. Comparison of Sagittal FSE T2, STIR, and T1-Weighted Phase-Sensitive Inversion Recovery in the Detection of Spinal Cord Lesions in MS at 3T. *AJNR Am J Neuroradiol.* 2016;37(5):970-975.
70. Vertinsky AT, Krasnokutsky MV, Augustin M, Bammer R. Cutting-edge imaging of the spine. *Neuroimaging Clin N Am.* 2007;17(1):117-136.
71. Griswold MA, Jakob PM, Heidemann RM, et al. Generalized autocalibrating partially parallel acquisitions (GRAPPA). *Magn Reson Med.* 2002;47(6):1202-1210.
72. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. *Magn Reson Med.* 1999;42(5):952-962.

73. Heidemann RM, Ozsarlak O, Parizel PM, et al. A brief review of parallel magnetic resonance imaging. *Eur Radiol.* 2003;13(10):2323-2337.
74. Larkman DJ, Nunes RG. Parallel magnetic resonance imaging. *Phys Med Biol.* 2007;52(7):R15-55.
75. Ruel L, Brugieres P, Luciani A, Breil S, Mathieu D, Rahmouni A. Comparison of in vitro and in vivo MRI of the spine using parallel imaging. *AJR Am J Roentgenol.* 2004;182(3):749-755.
76. Fruehwald-Pallamar J, Szomolanyi P, Fakhrai N, et al. Parallel imaging of the cervical spine at 3T: optimized trade-off between speed and image quality. *AJNR Am J Neuroradiol.* 2012;33(10):1867-1874.
77. Andre JB, Bammer R. Advanced diffusion-weighted magnetic resonance imaging techniques of the human spinal cord. *Top Magn Reson Imaging.* 2010;21(6):367-378.
78. Wilm BJ, Gamper U, Henning A, Pruessmann KP, Kollias SS, Boesiger P. Diffusion-weighted imaging of the entire spinal cord. *NMR Biomed.* 2009;22(2):174-181.
79. Kim TH, Zollinger L, Shi XF, et al. Quantification of diffusivities of the human cervical spinal cord using a 2D single-shot interleaved multisection inner volume diffusion-weighted echo-planar imaging technique. *AJNR Am J Neuroradiol.* 2010;31(4):682-687.
80. Sapkota N, Shi X, Shah LM, Bisson EF, Rose JW, Jeong EK. Two-dimensional single-shot diffusion-weighted stimulated EPI with reduced FOV for ultrahigh-b radial diffusion-weighted imaging of spinal cord. *Magn Reson Med.* 2017;77(6):2167-2173.
81. Frost R, Jezzard P, Douaud G, Clare S, Porter DA, Miller KL. Scan time reduction for readout-segmented EPI using simultaneous multislice acceleration: Diffusion-weighted imaging at 3 and 7 Tesla. *Magn Reson Med.* 2015;74(1):136-149.
82. Hayes LL, Alazraki A, Wasilewski-Masker K, Jones RA, Porter DA, Palasis S. Diffusion-weighted Imaging Using Readout-segmented EPI Reveals Bony Metastases from Neuroblastoma. *J Pediatr Hematol Oncol.* 2016;38(7):e263-266.
83. Beslow LA, Ichord RN, Zimmerman RA, Smith SE, Licht DJ. Role of diffusion MRI in diagnosis of spinal cord infarction in children. *Neuropediatrics.* 2008;39(3):188-191.
84. Talbott JF, Nout-Lomas YS, Wendland MF, et al. Diffusion-Weighted Magnetic Resonance Imaging Characterization of White Matter Injury Produced by Axon-Sparing Demyelination and Severe Contusion Spinal Cord Injury in Rats. *J Neurotrauma.* 2016;33(10):929-942.
85. Choudhri AF, Whitehead MT, Klimo P, Montgomery BK, Boop FA. Diffusion tensor imaging to guide surgical planning in intramedullary spinal cord tumors in children. *Neuroradiology.* 2014;56(2):169-174.
86. Kumar KA, Peck KK, Karimi S, et al. A Pilot Study Evaluating the Use of Dynamic Contrast-Enhanced Perfusion MRI to Predict Local Recurrence After Radiosurgery on Spinal Metastases. *Technology in Cancer Research & Treatment.* 2017;0(0):1533034617705715.
87. Yoshizawa T, Nose T, Moore GJ, Sillerud LO. Functional magnetic resonance imaging of motor activation in the human cervical spinal cord. *Neuroimage.* 1996;4(3 Pt 1):174-182.
88. Kornelsen J, Mackey S. Potential clinical applications for spinal functional MRI. *Curr Pain Headache Rep.* 2007;11(3):165-170.
89. Wheeler-Kingshott CA, Stroman PW, Schwab JM, et al. The current state-of-the-art of spinal cord imaging: applications. *Neuroimage.* 2014;84:1082-1093.
90. Martin AR, Aleksanderek I, Cohen-Adad J, et al. Translating state-of-the-art spinal cord MRI techniques to clinical use: A systematic review of clinical studies utilizing DTI, MT, MWF, MRS, and fMRI. *Neuroimage Clin.* 2016;10:192-238.
91. Erdem LO, Erdem CZ, Acikgoz B, Gundogdu S. Degenerative disc disease of the lumbar spine: a prospective comparison of fast T1-weighted fluid-attenuated inversion recovery and T1-weighted turbo spin echo MR imaging. *Eur J Radiol.* 2005;55(2):277-282.
92. Lavdas E, Vlychou M, Arikidis N, Kapsalaki E, Roka V, Fezoulidis IV. Comparison of T1-weighted fast spin-echo and T1-weighted fluid-attenuated inversion recovery images of the lumbar spine at 3.0 Tesla. *Acta Radiol.* 2010;51(3):290-295.
93. Melhem ER, Israel DA, Eustace S, Jara H. MR of the spine with a fast T1-weighted fluid-attenuated inversion recovery sequence. *AJNR Am J Neuroradiol.* 1997;18(3):447-454.
94. Phalke VV, Gujar S, Quint DJ. Comparison of 3.0 T versus 1.5 T MR: imaging of the spine. *Neuroimaging Clin N Am.* 2006;16(2):241-248, ix.
95. Eito K, Waka S, Naoko N, Makoto A, Atsuko H. Vertebral neoplastic compression fractures: assessment by dual-phase chemical shift imaging. *J Magn Reson Imaging.* 2004;20(6):1020-1024.

96. Erly WK, Oh ES, Outwater EK. The utility of in-phase/opposed-phase imaging in differentiating malignancy from acute benign compression fractures of the spine. *AJNR Am J Neuroradiol.* 2006;27(6):1183-1188.
97. Ragab Y, Emad Y, Gheita T, et al. Differentiation of osteoporotic and neoplastic vertebral fractures by chemical shift {in-phase and out-of phase} MR imaging. *Eur J Radiol.* 2009;72(1):125-133.
98. Yagmurlu B, Erden I, Tanju S, Genc Y. Opposed phase imaging in lumbar disc disease: an option providing faster image acquisition times. *J Magn Reson Imaging.* 2007;26(6):1578-1584.
99. Zajick DC, Jr., Morrison WB, Schweitzer ME, Parellada JA, Carrino JA. Benign and malignant processes: normal values and differentiation with chemical shift MR imaging in vertebral marrow. *Radiology.* 2005;237(2):590-596.
100. American College of Radiology. ACR Practice Parameter for Communication of Diagnostic Imaging Findings. 2014; Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/CommunicationDiag.pdf. Accessed October 2, 2018.
101. American College of Radiology. ACR-AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging (MRI) Equipment. 2014; Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/MR-Equip.pdf. Accessed October 2, 2018.

---

*Practice parameters and standards are published annually with an effective date of October 1 in the year in which amended, revised or approved by the ACR Council. For parameters and technical standards published before 1999, the effective date was January 1 following the year in which the practice parameter or technical standard was amended, revised, or approved by the ACR Council.

Development Chronology for this Practice Parameter
2019 (Resolution 5)
Amended 2023 (Resolution 2c)