ACR–ASNR–SABI–SSR PRACTICE PARAMETER FOR THE PERFORMANCE OF MAGNETIC RESONANCE IMAGING (MRI) OF THE ADULT 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.

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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 revised collaboratively by the American College of Radiology (ACR), the American Society of Neuroradiology (ASNR), the Society of Advanced Body Imaging (SABI), and the Society of Skeletal Radiology (SSR).

Magnetic resonance imaging (MRI) of the spine is a powerful tool for the diagnosis, evaluation, and follow-up of spinal disease. Spine MRI should be performed only for a valid and appropriate medical reason. Although spine MRI is one of the most sensitive diagnostic tests for detecting abnormalities of the spine and adjacent structures,

findings may be misleading if not correlated with the clinical history, clinical examination findings, and physiologic tests. Adherence to the following practice parameters will enhance the probability of detecting such abnormalities for accurate diagnoses.

MRI facilitates assessment of spinal disease without using ionizing radiation. It provides direct multiplanar visualization of all spinal components including the spinal cord and nerve roots, intervertebral discs, vertebrae, uncovertebral joints, facet joints, and spinal ligaments. Other diagnostic imaging tests of the spine such as radiography, computed tomography myelography, combined CT-myelography, and nuclear medicine examinations expose patients to ionizing radiation. Myelography also requires a lumbar puncture to introduce intrathecal contrast agent, and both the puncture and the contrast agent can cause complications. The location and morphology of the spinal cord and nerve roots can only partially be evaluated on computed tomography (CT), myelography, or CT-myelography. MRI allows direct visualization of these structures. It is the best overall diagnostic modality for evaluating the integrity of the spinal cord. MR neurography can further delineate the extraspinal course of the cervical and lumbosacral nerve roots. Ultrasound uses no ionizing radiation but is limited in spine evaluation due to inherent limitations of the technique in evaluating deeper structures and limited acoustic window of the adult spine. Ultrasound is useful in pediatric patients to evaluate paraspinal soft tissues and extraspinal nerves (eg, the brachial plexus) and for spinal cord and cauda equina assessment in infants.

Despite its superior soft-tissue contrast, MRI has not supplanted CT for osseous evaluation of the spine. CT provides fast and more conspicuous visualization of osseous detail than MRI and is the standard for cross-sectional evaluation of traumatic injuries and bony fusion, particularly in the presence of metallic hardware. Patients may have contraindications to undergoing MRI. Spinal MRI and CT may frequently provide complementary information for complex and/or indeterminant pathology.

II. INDICATIONS

This section includes many but not all of the reasons to perform spine MRI. Disorders affecting the spine that may warrant MRI including the following :

1. Congenital spine and spinal cord malformations

2. Degenerative conditions
    a. Degenerative disc disease and its sequelae in the lumbar, thoracic, and cervical spine, including myelopathy
    b. Extension of disc beyond the vertebral body—bulge, herniation-, protrusion, extrusion, sequestration (depending on appearance and terminology used)
    c. Radiculopathy
    d. Neurodegenerative disorders, including but not limited to subacute combined degeneration, spinal muscular atrophy, and amyotrophic lateral sclerosis

3. Trauma

    To assess the nature and extent of injury to the spinal cord, vertebral column, ribs, and skull base; ligaments, thecal sac, and paraspinal soft tissues. (CT is considered the primary tool for the initial evaluation of the traumatized spine, whereas MRI is often performed to provide complementary data; eg, detection of epidural hematoma, and compromise and/or injury of the spinal cord, thecal sac, and nerve roots, particularly when the patients' clinical findings are discrepant from the initial CT findings.)

4. Infectious conditions
    a. Discitis, vertebral osteomyelitis, epidural abscess, and surrounding soft-tissue infection, including postoperative infections
    b. Spinal cord infection and inflammation, including abscess

5. Neoplastic abnormalities

a. Intramedullary masses
b. Intradural-extramedullary masses, including leptomeningeal disease
c. Bone tumors
d. Other extradural soft-tissue neoplasms of regional nerves, muscles, and connective tissues

6. Radiation therapy
    a. Planning for treatment fields for radiation therapy
    b. Postradiation changes (eg myelopathy)

7. Inflammatory/autoimmune disorders
    a. Demyelinating disease
        i. Multiple sclerosis (MS) and its variants
        ii. Myelin oligodendrocyte glycoprotein antibody-associated disease
        iii. Neuromyelitis optica spectrum disorder
        iv. Acute disseminated encephalomyelitis
        v. Acute inflammatory demyelinating polyradiculopathy (Guillain-Barre syndrome)
        vi. Chronic inflammatory demyelinating polyradiculopathy, also known as chronic relapsing polyneuropathy
    b. Connective tissue disorders (eg systemic lupus erythematosus)
    c. Muscular dystrophies and myopathies

8. Vascular disorders
    a. Spinal vascular malformations and/or the cause of occult subarachnoid hemorrhage
    b. Spinal cord infarction
    c. Extraspinal vascular malformations

9. Postprocedural evaluation including
    a. Postoperative fluid collections and soft-tissue changes (extradural and intradural)
    b. Epidural and subdural fluid collection

10. Miscellaneous
    a. Syringohydromyelia (multiple etiologies, including Chiari malformations, trauma, and tumor, etc)
    b. Preprocedure assessment for vertebroplasty and kyphoplasty
    c. Amyloid deposition in the spine
    d. Spinal cord herniation
    e. Cerebrospinal fluid (CSF) leak, spontaneous intracranial hypotension
    f. Gout
    g. Symptoms that create the concern for the presence of any of the above disorders
    h. Follow-up of incidental or concerning findings seen on other imaging examinations

III. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [1].

IV. APPLICATIONS OF MRI

A. Congential Abnormalities

Congenital abnormalities of the spine and spinal cord can be detected on screening tests of spinal curvature (scoliosis), in patients with clinical suspicion, or incidentally. MRI of the entire spine can be used as a screening test for anomalies.

Scoliosis cases may require multiple acquisitions or reformatted images with compound and/or complex angles to cover the areas of concern. Coronal large field-of-view (FOV) series, especially T2W imaging, are specifically useful in characterizing and fully displaying spinal curvature, as well as assessing for vertebral anomalies. Alternatively, 3-D isotropic T2W fast spin-echo (FSE)/turbo spin-echo (TSE) can be obtained for multiplanar assessments. T1W imaging is helpful for detection of associated fatty infiltration of the filum, dermoid/teratoma

and lipoma, and so on. Prone imaging may be useful in evaluation for tethered cord, especially when clinical or evaluation on conventional supine sequences is equivocal.

IV. APPLICATIONS OF MRI

B. Degenerative Disc Disease

MRI provides a precise representation of the anatomy and the degenerative conditions of the disc, spinal canal, discovertebral complex, uncovertebral joints, and facet joints to render an accurate diagnosis of degenerative disc disease and influence therapeutic decision-making [2]. MRI is well established as the modality of choice for evaluating degenerative disease of the spine, although in select patients, CT with or without myelography and gradient-echo imaging may provide complementary and alternative information such as distinguishing between disc and bone [3]. MRI can also be used for new, recurrent, or persistent symptoms after surgery [4,5].

IV. APPLICATIONS OF MRI

C. Spinal Stenosis

The anatomic assessment provided by MRI allows for accurate evaluation of both acquired and developmental spinal stenosis [6,7]. MRI can assess the morphology of the spinal canal and foramina and can characterize the presence, location, and cause of stenosis [8,9].

IV. APPLICATIONS OF MRI

D. Trauma [10-20]

MRI is a valuable tool for assessing patients with known or suspected injury. In addition to assessing the fractures and their extent and acuity, it can aid in evaluating the integrity of ligaments, which are critical to spinal stability. It also contributes to imaging the spinal cord for transection, contusion, edema, and hematoma. Cord compression by bone fragments, disc herniation, and epidural or subdural hematomas can also be demonstrated. Serial examination of patients with hemorrhagic cord contusion can evaluate for progressive posttraumatic myelopathy.

MRI is also useful in patients with equivocal findings on CT examinations by searching for evidence of occult soft-tissue injury (edema, ligament disruption) as well as bone contusion (trabecular microfracture). In instances of cervical trauma, MR imaging and MR angiography (MRA) can screen for vertebral and carotid arterial injury.

IV. APPLICATIONS OF MRI

E. Infection

In a patient with suspected spinal infection, MRI demonstrates high sensitivity and specificity compared with radiographs and bone scans [21-23]. It can localize the site(s) of infection (eg, within the disc space, vertebral bodies, or both), assess the extent of epidural and paravertebral involvement, and determine presence of an abscess [21,24]. Given the ability to perform large FOV series, it is ideally suited to identify or exclude additional, potentially clinically occult sites of infection in the remaining portions of the vertebral column. Intravenous administration of gadolinium-based contrast agents increases the sensitivity, conspicuity, and observer confidence in the diagnosis of abscess, especially in early stages, and is useful to distinguish abscess from phlegmon [21,22].

Diffusion-weighted imaging (DWI) MRI of the spine may help differentiate spinal discitis-osteomyelitis from Modic type I degenerative endplate edema and does not require the administration of intravenous contrast [25,26]. CT may give complementary information regarding bony architecture such as degenerative disc vacuum phenomenon, endplate sclerosis, and lytic erosions.

MRI can also diagnose and characterize the presence of infections in other spinal regions, such as the facet joints, meninges, and spinal cord. MRI is useful to characterize postoperative changes, including fluid collections and bone and soft-tissue abnormalities that may suggest infection.

IV. APPLICATIONS OF MRI

F. Neoplasms

MRI is an excellent way of defining local tumors of the spine. It defines anatomy, and, because of its ability to differentiate tissue types, it can be used to characterize tumors and suggest histologic diagnoses.

In the evaluation of intraspinal soft-tissue tumors, MRI can localize disease to various compartments (intramedullary, intradural-extramedullary, and extradural), which is an important step in creating differential diagnoses and planning for surgery. CT is complementary for evaluating osseous involvement and mineralization within tumors. MRI is well suited for delineating intraspinal lesions, assessing extent within and outside the spinal canal, and evaluating the extent of spinal cord and spinal nerve involvement. The administration of intravenous gadolinium-based contrast agents may improve sensitivity for lesion detection and characterization. Almost all intramedullary spinal cord tumors enhance following the administration of intravenous gadolinium [27].

In addition to spinal soft-tissue tumor evaluation, MRI provides an assessment of primary and metastatic osseous neoplasms involving the vertebral column. It helps demonstrate not only the presence and extent of bony involvement but also the presence and location of epidural and paravertebral extension and the degree of spinal cord and foraminal nerve root compression. Overall, MRI appears to be more sensitive than bone scintigraphy using single-photon emission computed tomography for detecting metastatic disease [28-30] but may not be as sensitive for detecting small metastases in the posterior elements [29]. MRI is also more sensitive and specific than flourine-18 fluorodeoxyglucose positron emission tomography (18F-FDG-PET) (but slightly less sensitive and specific than fluorine 18–sodium fluoride positron emission tomography/ computerized tomography [18F-NaF PET/CT]) for detecting bone marrow metastases and infiltration of the spine and can help with cancer staging [31,32]. As described below, chemical shift imaging may be useful for distinguishing between benign and malignant bone marrow pathologies. In the setting of multiple myeloma screening, DWI can be a valuable additional pulse sequence [33].

IV. APPLICATIONS OF MRI

G. Changes from Radiation therapy to the Spine

Radiation therapy has been a mainstay of treatment of neoplastic diseases, but unfortunately, it can result in unintended effects. These effects can involve both the vertebral column and spinal cord.

In the vertebral column, the most benign changes are well seen by MRI and initially consist of marrow edema, followed by fatty replacement of the marrow. These changes can occur as soon as a few weeks after the cessation of radiation therapy. More serious effects include radiation osteonecrosis [34,35]. CT is complementary for evaluating for demineralization. Radiation osteonecrosis is most common after treatment for head and neck tumors, although it can be seen following radiation therapy for other neoplasms (such as in the pelvis). Radiation osteonecrosis can result in collapse of the involved vertebral body. MRI is superb in localizing the involved bones and can suggest the diagnosis of radiation injury (which can occur only if the area of pathology was treated with radiation). MRI with intravenous gadolinium may be useful to differentiate treatment changes from viable residual or recurrent neoplasm in the spine. Superimposed osteomyelitis may complicate the clinical scenario [36].

Radiation therapy can also induce complications of radiation myelopathy and neuropathy [37-46]. Acute radiation myelopathy may show cord edema but may not produce conspicuous MR findings. Later stages of radiation myelopathy typically result in mass effect, swelling, and solid or rim enhancement in the subacute phase that may be followed by atrophy in the chronic phase [44]. MRI is particularly suited to diagnose radiation myelopathy due to its ability to depict the underlying cord lesion, with characteristic ring enhancement associated with radiation changes in the spinal column, ranging from fatty infiltration to radiation-induced bone infarcts and necrosis.

Radiation therapy can lead to the development of treatment-related tumors several years to several decades later [47]. These include bony neoplasms of the bones, such as osteochondroma or osteosarcoma, as well as the soft tissues including intradural-extramedullary tumors, such as meningiomas, and cord gliomas. Again, MRI can portray the association of the neoplasm with the classic changes of prior radiation exposure to the vertebral column.

IV. APPLICATIONS OF MRI

H. Demyelinating Diseases

MR imaging is the examination of choice for the imaging diagnosis and follow-up of demyelinating processes affecting the spinal cord. MRI is the best available technique for identifying the extent of disease, although lesion burden does not correlate well with clinical status in patients with MS [48]. However, spinal cord cross-sectional area may correlate with clinical disability [49]. Additional techniques may make MS plaques more conspicuous, including proton density, short tau inversion recovery (STIR), other fat suppression, and gradient-echo techniques [50-54]. Advanced MR imaging techniques, such as diffusion tensor imaging and spectroscopy, may become valuable adjuncts [48,55,56].

Brain imaging is typically performed if a spinal cord abnormality suggests a demyelinating disease. Other types of demyelinating lesions such as acute disseminated encephalomyelitis, neuromyelitis optica spectrum disorder, myelin oligodendrocyte glycoprotein antibody-associated disease, and idiopathic transverse myelitis have patterns of spinal cord involvement that inform the differential diagnosis [57].

IV. APPLICATIONS OF MRI

I. Vascular Lesions of the Spine

Multiple vascular lesions can affect the spine. There are two general categories: ischemia and vascular malformations. MRI is the most sensitive method of verifying the presence of cord abnormalities that may represent ischemia and infarction [58-60]. As in the brain, DWI is particularly sensitive and diagnostic in the appropriate clinical settings. Conventional MRI, however, can also demonstrate classic findings of cord infarction, with an abnormal T2 signal acutely involving the anterior half to two-thirds of the cord or being centered primarily in the grey matter. Due to the small size of collaterals vessels that feed the cord, MRA is generally not useful in this clinical setting.

Vascular malformations include arteriovenous fistulas (including dural arteriovenous fistulas [dAVFs]), arteriovenous malformations (AVMs), and cavernous malformations [61-65]. Multiple findings can be seen, including a characteristic intramedullary lesion in a cavernous malformation, a nidus of serpentine signal voids in AVMs, or posteriorly draining enlarged veins in dAVFs. In addition, MRI is also sensitive to secondary changes in the cord, such as edema from venous congestion. Time-resolved MRA, generally performed with intravenous contrast, is particularly helpful. It helps detect and characterize these lesions [65], depicts the presence of an arteriovenous shunt, and guides subsequent spinal angiography.

Occult vascular malformations, as in the brain, generally appear as focal lesions containing byproducts of hemoglobin degradation [61]. In most cases, virtually no surrounding edema is present, unless there has been recent bleeding. Using sequences sensitive to local variations in magnetic susceptibility, MRI is the most sensitive technique available for detecting suspected cavernous malformations. In addition, the absence of surrounding cord swelling, and edema are also well depicted on MRI, allowing differentiation from neoplasms.

IV. APPLICATIONS OF MRI

J. Spinal Cord Herniation

Spinal cord herniation is a rare but important cause of myelopathy. If addressed in a timely fashion by surgery, symptoms are reversible [2,3,66,67]. MRI helps demonstrate the location of the cord herniation through an associated dural defect, assess the degree of herniation, and determine if there are any cord signal changes, all of which impact patient management and prognosis [2,3,66,67]. The MRI appearance may not be pathognomonic for a spinal cord herniation because it may be difficult to distinguish from an arachnoid web or arachnoid cyst. CT myelography can play a complementary role in cases of suspected spinal cord herniation to differentiate it from a thoracic web or arachnoid cyst [68]. Dorsal thoracic arachnoid web has a characteristic "scalpel" appearance that can be diagnosed on MRI or CT myelography [69].

Application of this practice parameter should be in accordance with the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) and the ACR–SIR Practice Parameter for Minimal and/or Moderate Sedation/Analgesia [1,70].

V. SPECIFICATIONS OF THE EXAMINATION

The supervising physician must have adequate understanding of the indications, risks, and benefits of the examination, as well as imaging options . The physician must be familiar with potential hazards associated with MRI including potential adverse reactions to contrast media. Potential hazards might include implanteddevices. The interpreting physician should be familiar with relevant ancillary studies that the patient may have undergone. The physician must have a clear understanding and knowledge of the anatomy and pathophysiology relevant to the MRI examination.
The written or electronic request for MRI of the adult 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's scope of practice requirements. (ACR Resolution 35 adopted in 2006 – revised in 2016, Resolution 12-b) Information provided by the patient, including history, symptomatology, and a pain diagram, can be useful to direct interpretation of examinations.

The supervising physician must also understand the imaging parameters, including pulse sequences and FOVs, 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 . 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.

Certain indications require administration of intravenous contrast media. Intravenous contrast enhancement should be performed using appropriate injection protocols and in accordance with the institution's policy on intravenous contrast utilization. (See the ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media [71].)

Patients suffering from anxiety or claustrophobia may require sedation or additional assistance. The 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 [70].

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

MRI should depict structures as clearly as possible. Standard protocols that are appropriate for most patients 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 body habitus, and the personal

preferences of the radiologists who manage and interpret the studies. Generally, images should cover the relevant anatomy/pathology. Coil selection and FOV will depend on patient size and the region imaged. A spine coil should be considered while larger patients may be imaged with a cardiac, torso, spine, or body coil. Commercially available combined coil arrays may also be suitable.

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 intravenous administration of a paramagnetic MR contrast agent (eg, a gadolinium chelate). This agent is used to detect regions where the normal vascular circulation has been altered by injury or disease. For example, the use of intravenous paramagnetic contrast is recommended for distinguishing disc material from scar tissue in patients who have undergone spinal surgery, especially in the first few years following surgery [72].

Artifacts

Imaging sequences should minimize artifacts as much as possible.

Physicians and technologists who determine the pulse sequences to be used and 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) that are likely to obscure pathology. Some techniques used to mitigate artifacts include changing phase and frequency directions (to move pulsation artifact), increasing resolution (to reduce frequency mis-registration), applying saturation bands or flow sensitization preparation pulses (for CSF or blood), gating techniques, and modifying patient/coil positions to improve comfort and reduce respiration and other motion artifact .

When imaging around metal, such as fixation devices, STIR for fat suppression, short time to echo (20-30 ms), decreased slice thickness/small voxel size, high-receiver bandwidth, fat-water separation, low echo spacing (high echo train lengths), and special (sometimes vendor, hardware, and software-dependent) metal artifact reduction sequences may be helpful to reduce artifacts [73]. Examination at 1.5T rather than with higher strength 3T magnets may be preferred in patients with spine hardware to reduce susceptibility artifacts.

V. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

2. Pulse sequences

The choice of MR pulse sequences is generally standardized for particular studies but should be guided by the clinical question (see section III, Indications). Commonly used sequences in MR imaging of the spine include T1 or T1 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. The 3-D acquisitions can be formatted into multiple planes. Vascular techniques can be used for angiography. Fat suppression can be achieved with a variety of techniques including chemical shift based, inversion pulse based, specific frequency selection, and hybrid techniques [74]. Although these techniques are not all inherently T2-weighted, they can substitute for the T2-weighted sequences noted below if they provide sufficient fluid sensitivity.

Additional sequences that may be useful for problem solving include heavily T2-weighted sequences without pulsation artifact (such as 3D T2 CUBE/SPACE or FIESTA/CISS). They provide high spatial resolution and excellent contrast between cerebrospinal fluid (CSF) and soft tissue and may improve visualization of nerve roots, blood vessels, arachnoid adhesions, and arachnoid cysts with spinal CSF (Li Z, Chen YA, Chow D, Talbott J, Glastonbury C, Shah V. Practical Application of CISS MRI in Spine Imaging. Eur J Radiol Open. 2019; 6: 231-242. PMID 31304197.)

For the purpose of comparison or subtraction, images with fat suppression are sometimes acquired both before and after administration of the intravenous contrast agent.

T2* or gradient-echo images provide high 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 due to brisk or pulsatile CSF flow). They can be useful to distinguish disc versus osteophyte, especially in cervical spine imaging.

Given anatomical and physiological differences in three major spinal regions, radiologists may prefer to use different sequences in different regions. In the cervical and thoracic spine, CSF flow rate is greater than in the lumbosacral spine. T2*-weighted images are apt to incur less CSF flow–related artifacts than are T2-weighted FSE images.

In the cervical spine, where neural foramina are small and obliquely oriented , direct oblique imaging or a T2 isotropic acquisition with reformations may improve the detection and characterization of neural foraminal pathology. CT provides additional information about bony proliferation that may narrow the neural foramina. Newer MR techniques such as Zero-Echo-Time may improve visualization of bony neural foraminal stenosis and potentially obviate the need for concurrent CT.

MR imaging of any portion of the spine should include T1- and T2-weighted sequences, preferably in 2 planes with slice thickness dependent on the area to be imaged (usually up to 5 mm). T2* sequences can be helpful, especially in the thoracic and cervical spine, to evaluate for disc protrusions and bony stenosis.

In postoperative cases when trying to differentiate scar from disc, postcontrast T1- weighted sequences, with or without fat suppression, are useful. Coronal sequences may also be helpful, particularly in a postoperative patient who had an operation for a foraminal or extraforaminal disc herniation.

When evaluating spinal bone marrow for tumor, sagittal T1-weighted sequences should be performed. Chemical shift imaging can be helpful to distinguish between benign and malignant lesions, as discussed below. Fat-suppressed T2-weighted or STIR 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 extension of a neoplastic process.

V. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

3. Slice Thickness

Generally cervical spine sagittal/axial slice thickness should be =3 mm. Thoracic and lumbar spine slice thickness should be sagittal/axial slices =4 mm. Newer techniques with isovolumetric acquisitions can bring slice thickness below 1 mm.

Slice thickness may depend on the area covered and the clinical scenario. For example, when evaluating for a pars interarticularis defect, 3-mm or less sections in the sagittal plane may be warranted. When attempting to detect and characterize spinal cord pathology, 2-mm sections may be appropriate. When covering large areas, such as for screening of congenital abnormalities, slice thickness may be greater. Interslice gaps will depend on hardware and software but are generally not recommended because contiguous imaging has the advantage of not excluding any anatomy.

V. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

4. Area of Coverage

The imaging protocol would ideally be designed to cover the area of clinical interest. In addition, technologists may further evaluate areas of pathology identified on scans while they are being performed. It is recommended that an additional physician's order be obtained if the scope of the additional area includes a completely separate body region. Studies may need to be tailored to patients' tolerances.

Routine imaging, for example, pain, radiculopathy, suspected stenosis, or other degenerative conditions:

Cervical spine: Sagittal images would ideally cover from the skull base through at least the C7-T1 intervertebral disc and extend through the neural foramina on both sides. The axial images should have contiguous slices at least from C2-3 through C7-T1.

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 would ideally 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 and go through the neural foramina on both sides. In patients being evaluated for disc pathology, axial images should be approximately parallel to the discs. 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 multiple acquisitions in patients with significant thoracic kyphosis). Coronal imaging, if performed, should include the exiting nerves in the area of concern, as well as the proximal ribs.

For thoracic imaging, visualization of the C2-3 disc or the first thoracic rib can be useful for the accurate localization of thoracic levels and pathology. The upper cervical spine can be obtained on a separate low-resolution sagittal sequence.

Lumbar spine: The entire lumbar spine should be imaged sagittally and include the entire neural foramina and immediate paraspinal soft tissue (T12 to S1). Contiguous axial images (not just through the discs) should be obtained through at least the lowest three lumbar discs (L3-4, L4-5, and L5-S1) and preferentially also L1-2 and L2-3. The stacked axial images should be as perpendicular to the spinal canal and parallel to the disc spaces as possible, and typically 2 or 3 overlapping axial sequences or reformatted images are needed to cover all lumbar segments. If 3-D or isotropic voxels are used, axial images can be reformatted to be approximately parallel to the discs. 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.

For tumor and infection, sagittal and axial images should include the area of clinical interest, and fat suppression on the postcontrast images may be helpful. If other imaging modalities or the clinical evaluation narrow the levels of suspected abnormalities, then it may be appropriate to limit an 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.

Screening:

Occasionally, screening of the entire spine is performed to look for anatomic variations and evaluate systemic syndromes or multifocal disease. In these situations, larger FOVs and thicker slices may be appropriate, with or without more detailed imaging of selective areas identified as pathologic. Screening of the spinal cord to exclude compression or lesions may also use larger FOVs.

Other techniques that may be relevant:

a. Parallel Imaging (PI)

PI uses the spatial sensitivity information from phased-array radiofrequency coils to reduce the number of phase-encoding steps and therefore shortens the time of image acquisition. These time savings imply a loss of signal-to-noise ratio, but without compromising image contrast or spatial resolution. The coil sensitivity information is obtained by performing a prescan calibration or by obtaining additional lines of k-space with each sequence as "auto calibration." Numerous image reconstruction algorithms have been developed, including space domain–based techniques (SENSE, ASSET) and k-space regenerative techniques (ARC and GRAPPA). The maximum reduction in imaging time, reflected in the PI acceleration factor, is typically =2 . The limitation of the accelerating factor is due to increased noise associated with both reduced temporal averaging and the reconstruction process. The reduction in signal-to-noise ratio associated with higher PI factors can be counterbalanced by the increased signal-to-noise ratio at higher fields, improved surface coils, and advanced acquisition schemes. When imaging a small FOV, the sensitivity maps may be used to reduce wraparound artifact if the images are acquired without reduced k-space sampling.

PI is applicable to most 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. In 3-D imaging, the phase-encoding steps can be reduced in 2 directions, for PI factors of approximately 4 . Coronal plane reconstruction from 3-D imaging may be helpful for evaluating scoliosis and extraforaminal disease. These techniques have been used to create fast imaging protocols, for example, to reduce the need for anesthesia in children [75].

b. CSF flow imaging of the spine [76-79]

CSF flow can be imaged with phase-contrast cine MRI evaluation. Cardiac gating with either electrocardiogram 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. Spinal CSF flow imaging is performed in the axial and/or sagittal planes.

Common indications for phase-contrast cine imaging in the spine include evaluation of flow dynamics at the craniocervical junction in patients with Chiari I malformation as well as craniocervical and whole-spine imaging of patients with idiopathic syringomyelia in the search for myelographically occult arachnoid cysts or webs.

c. T1-FLAIR versus T1 FSE imaging of the spine [80-83]

T1 FSE/TSE is a routine pulse sequence for imaging of the spine and can provide anatomic detail within a relatively short acquisition time compared with conventional spin-echo imaging. Fast T1-FLAIR imaging takes advantage of short image acquisition with T1 weighting as well as suppression of CSF signal. Although both T1 FSE/TSE and fast T1-FLAIR of the spine are useful for demonstrating normal anatomic structures and determining the presence of both degenerative and neoplastic processes of the spine, there are advantages to using fast T1-FLAIR imaging of the spine at higher magnetic field strengths. The 3T fast T1-FLAIR imaging appears to allow for superior conspicuity of normal tissue interfaces as well as spinal cord lesions and abnormal vertebral body marrow at 3T. Due to increased T1 values at higher magnetic field strengths that result in reduced T1 contrast, fast T1-FLAIR has improved CSF nulling and higher contrast-to-noise ratios, compared with T1 FSE/TSE. Additionally, there is a reduction in susceptibility artifacts from the presence of metallic hardware using T1-FLAIR compared with T1 FSE/TSE. T1-FLAIR may also reduce specific absorption rate, which can be a limiting factor at higher fields.

d. Chemical shift imaging [84-88]

Chemical shift imaging, also known as opposed-phase or in-and-out-of-phase imaging, is a modality 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 be used to aid in distinguishing between marrow-replacing processes and marrow-preserving processes [89]. 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 malignant ones [90]. The T1-weighted gradient echo (GRE) sequences can be rapidly acquired, with a total scanning time of less than 5 minutes. Chemical shift imaging can also be used as a technique for fat suppression.

e. Perfusion

MR perfusion-weighted imaging (PWI) has enjoyed great clinical and research success in the assessment of cerebrovascular reserve and as an adjunct for assessing biologic behavior of cerebral neoplasms. PWI uses rapid data acquisition techniques to generate temporal data series that capture the first pass kinetics of a contrast agent as it passes through a tissue matrix. PWI uses 3 general contrast mechanisms: (1) dynamic susceptibility contrast, which is sensitive to transient changes in magnetic susceptibility caused by a contrast bolus; (2) dynamic contrast enhancement, which tracks T1 changes caused by intravenous contrast; and (3) arterial spin labeling, which does not require contrast administration and uses radiofrequency tagging of spins to depict blood flow. PWI has been less commonly used in the spine; however, several investigators have examined its potential in helping to discriminate spine lesions and to assess vascular reserve in the spinal cord.

In the setting of neoplasia, MR-PWI is thought to provide physiologic information about the microcirculation of tumors, with the PWI metrics being a direct reflection of angiogenesis, vascular density, and capillary permeability. It has also been used to discriminate pathologic and benign insufficiency fractures with variable success and, in conjunction with DWI, to improve the specificity in discriminating benign and malignant spine bone tumors [91,92]. Furthermore, it may help differentiate treated spinal neoplasm from recurrent or residual viable tumor [36].

Small case series have used PWI to assess spinal cord vascular reserve in specific clinical applications. It has also been used to predict outcomes of spinal metastases [93].

f. Dynamic imaging/motion studies

Dynamic MR of the spine is the natural extension of other types of imaging that attempt to visualize the relationships of the spinal components during physiologic loading or in varying positions. The most conventional form of imaging that is in common use historically is lateral flexion-extension radiography of the spine to assess for areas of segmental instability. Caution must be exercised in manipulating the cervical spine in patients with instability and trauma and those who are anesthetized. There are known alterations in spinal canal diameter and neural foraminal size between extremes of flexion and extension. Hyperextension produces buckling of the ligamentum flavum that can produce dynamic mechanical causes of cervical spondylotic myelopathy. Prior investigations principally used myelography and CT with intrathecal contrast media, although more recently MRI has been used.

Because MRI provides exceptional simultaneous soft-tissue and osseous detail in multiple imaging planes, it is a logical next approach to evaluate dynamic dimensional changes to the neural axis . However, capabilities to study the spine under physiologic load are limited on most conventional scanners. Although flexion/extension radiography is performed in the upright position to simulate physiologic loading, conventional MRI is performed recumbently. This deficiency has led to several technical developments 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. The latter is more limited because it does not facilitate imaging in extremes of position; rather, it only replicates normal physiologic load imposed by gravity in the upright position.

Upright MRI units can 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. A number of investigations have been performed using flexion/extension MRI to study changes in the disc/ligament complexes and their effect on the spinal cord and neural elements. Studies have shown correlation of changes with loading and motion with symptoms [94,95]. They may improve conspicuity of pathology, such as annular fissures and disc herniations. Compared with high-field MRI examinations, overall image quality may be reduced if a larger FOV, thicker sections, or a reduced matrix is employed.

Kinematic or dynamic imaging can be performed at 3T [96] and offers some intriguing physiologic information regarding potential segmental instability and dynamic impingement. As yet, there is very little evidence that this additional information correlates with individual patient symptoms or improves patient outcomes after therapy. Currently, access to kinematic or dynamic MRI is limited.

Flexion MRI can be useful for diagnosis of Hirayama disease and reveal flattening of the cord. This may be suspected clinically (often in a young patient with hand weakness) or by the radiologist when there is lower cervical cord signal abnormality without an obvious cause.

g. Angiography for vascular malformations:

Dynamic MRA can be performed for better evaluation of spinal vascular malformations [59, 60]. Images obtained as frequently as 0.5 seconds may be obtained while intravenous contrast is being administered to obtain time resolved information. Spatial resolution is improved by covering the spine in 2 FOVs. Spinal dAVFs yielding cord edema often have fistula points in the lumbosacral region, so yield is improved by first imaging the lower half of the spine. The upper half of the spine may be imaged with a second bolus immediately afterwards or at a later date if fistula point is not identified in the lower half of the spine.

h. Diffusion

Diffusion imaging has been used to image vertebral bodies , paraspinal soft tissues, and the spinal cord. For bone lesions, some authors have found poor sensitivity and specificity when diffusion imaging is considered in isolation but a useful adjunct to T1-weighted imaging when used in combination [97]. Smaller diffusion coefficients in osseous metastases than normal marrow have been attributed to higher cellular density in malignant than in benign conditions. For example, Byun et al reported perfect separation of sacral insufficiency fractures from metastases by diffusion MR [98]. Others have found no incremental contribution of diffusion to distinguishing benign from metastatic disease [99].

There is ample evidence that diffusion imaging is of similar value in the spine as in the brain. However, spinal diffusion imaging faces technical limitations . The most challenging are motion of the spinal cord and susceptibility artifacts that cause image distortion, particularly for echo planar approaches. Currently, popular solutions revolve around reduced FOV imaging, with 2 major approaches under active investigation. One method is to perform conventional excitation and suppress the signal from outside the desired FOV. These outer volume suppression methods have been successfully applied in spinal cord imaging, often with FSE acquisitions to further control susceptibility artifacts [100]. Another approach is to selectively induce signal only from the desired FOV. Several authors have also used these inner volume excitation methods; for example, the interleaved multisection inner volume approaches [101].

Spinal diffusion appears useful in the common clinical dilemma of differentiating discitis-osteomyelitis from degenerative endplate edema (Modic type I change) and detecting soft-tissue abscess. Endplate degenerative change often has a "claw-like” appearance with incomplete involvement of the vertebral body in contrast to discitis-osteomyelitis, in which the diffusion abnormality often involves the entirety of one or more vertebrae [25,26].

Using these methods, authors have applied diffusion-weighted spinal cord imaging to map the characteristics of normal tissue [102,103] in chronic spinal cord injury [103], cervical myelopathy [104],

intramedullary neoplasms [105], and demyelinating disease [106]. For nonneoplastic conditions, diffusion imaging aims to identify axonal and myelin injury. Diffusion tensor imaging can highlight axonal injury as seen as loss of fractional anisotropy. The application of tractography, to determine fiber direction, may be of lesser significance in the spinal cord, where fiber orientation is less complex compared with the brain.

Similar to the widespread applications of diffusion MRI to evaluate acute cerebral infarcts, spinal diffusion can detect spinal cord ischemia if performed in the acute presentation [107,108], albeit a much less common cause of abnormal cord signal than the aforementioned cord compression related to degenerative disease.

VI. ARTIFICAL INTELLIGENCE/MACHINE LEARNING

The use of artificial intelligence and machine learning in imaging is quickly advancing. Active research is leading to several areas in spine MRI to which techniques are being applied. There will likely be great variation in timing and scope of such applications. They include ordering, scheduling acquisition/reconstruction, presentation, interpretation/analysis, and reporting [75,109-111]. Work has specifically been done to evaluate deep-learning techniques to denoise both 2-D and 3-D data [112] for higher spatial resolution and faster imaging and to evaluate fractures [113] and degrees of stenosis [114].

VII. DOCUMENTATION

Reporting should be in accordance with the ACR Practice Parameter for Communication of Diagnostic Imaging Findings[115].

VIII. EQUIPMENT SPECIFICATIONS

Equipment performance monitoring should be in accordance with the ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance (MR) Imaging Equipment [116].

IX. 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).
See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI), the ACR Manual on Contrast Media, and the ACR Manual on MR Safety[1,117,118].

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

The quality of a study involves the quality of the images themselves and the interpretation, with technologist and radiologist expertise required for an optimal outcome.
Technologist quality
This section discusses the performance of the examination and measures that might be necessary on the technologist side that is not covered in the specifications section.
MRI is a somewhat user-dependent examination; a technologist's vigilance and knowledge are keys to creating the best examination possible using available equipment and responding to patient-specific imaging challenges. Coil selection, parameter selection, and patient positioning are important in the initial setup of a study, including appropriate localizer images to ensure proper coverage of the anatomy . Once images are reconstructed , the technologist must be able to identify artifacts and understand how to reduce them. Additional important roles of the technologist are to understand the clinical indication, to act as a check to ensure the study is performed appropriately for the given indication, to have a basic knowledge of the anatomical site of potential pathology, and to ask for help when uncertain. The hope is to meet all the patients' needs on the initial visit, but it is understood that patients may need to be recalled for further imaging.
Additional sequences may be necessary to distinguish between pathology and artifact (such as potentially abnormal cord signal).

Radiologist quality
The quality of an examination interpretation involves many aspects of interpretation including perception, disease understanding, and an environment that reduces interruption and promotes radiologist concentration. Both aspects require a systematic and rigorous evaluation of a good-quality examination [119].

Imaging examinations should be interpreted in a systematic and thorough fashion. What ends up in a report is often the preference of the interpreting physician, with some physicians being more detailed than others. Despite the form of a report or its content, the interpreting physician should see all reasonably detectable pathology and report clinically relevant pathology. A description of the alignment, discs, canal and foraminal stenosis, and what pathology contributes to each abnormality is typical in a report. It may not always be possible to distinguish between disc material and osteophyte.

In the spine, one of the most important causes of pain is mass effect on a nerve . Identification of compressed or displaced nerves and the location thereof, with an eye on defining the cause of a patient's pain, provides some of the most valuable information derived from spine MRI. Identification and descriptions of disc protrusions, extrusions, and sequestrations, although often subtle, are imperative for the MRI reader. Less common causes of pain include spinal cord and soft-tissue (eg, muscle) abnormalities. The facet joints should be evaluated as a source of pain, as should the sacroiliac joints included in the field of lumbar MRI.

Incidental imaged extraspinal pathology is important to identify in order to detect potential malignancies or other pertinent pathology on both diagnostic and localizer images. Congenital vascular abnormalities, aortic aneurysms, and retroperitoneal adenopathy may also be incidentally observed and should be reported.

Some diseases are particularly difficult to confirm on imaging, such as infection, and follow-up studies may be warranted for further investigation .

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 direction of a supervising MRI physician. Guidelines should be provided that deal with potential hazards associated with MRI examinations 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.

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