Magnetic Resonance Imaging of the Spine

Abstract

Historically, magnetic resonance imaging has offered poor specificity in the diagnosis of back pain. Researchers currently are engaged in developing new techniques, and clinicians are successfully utilizing existing technologies (ie, diffusion-weighted imaging) that previously were not used to evaluate the spine. Magnetic resonance imaging may be used in several spinal applications: intervertebral disk and facet joint degeneration, spinal canal stenosis, suspected diskitis or osteomyelitis, suspected spinal column neoplasia, vascular disorders, trauma, and demyelinating disease.

Magnetic resonance imaging (MRI) scans are produced from energy emitted by tissues and liquids (eg, fat, muscle, spinal cord, edema, cerebrospinal fluid [CSF]) after stimulation of their protons by radiofrequency (RF) waves in the presence of a magnetic field. Within the magnetic field, tissues and fluids acquire a weak magnetic force because a fraction of the protons (approximately 1/10^6) align preferentially with the magnetic field. The excitation of the aligned protons and the detection of the emitted energy is the basis for all MRI. A list of terms associated with MRI is presented in Table 1.

Stimulation Pulses and Signal Detection

A stimulation pulse is an RF pulse set at a frequency appropriate to permit the aligned protons to absorb energy. A 90° pulse changes the alignment of the protons by 90° relative to the main magnetic field; a 180° pulse changes the alignment by 180°. When the stimulation pulse is turned off, the excited protons relax to their initial state and emit a weak magnetic force that induces a small but detectable electromagnetic current in a receiver coil. This detected energy is called the free induction decay. The signal current is digitized, stored, and converted, through the Fourier transform, into an image. The amount of energy emitted and signal detected is proportional to the concentration of protons, the chemical and physical structure of the tissue, and the strength of the magnetic field. Stronger magnetic fields result in increased amounts of emitted energy and stronger signals.

The magnetic field strength can be adjusted by applying additional magnetic gradients to provide spatial localization. To create images, a region of interest is stimulated with multiple RF pulses repeated at specific intervals (TR) as the magnetic field is varied to excite protons. These signals are transformed into signal intensities as a function of position in space and are converted to gray scale for interpretation as an image.

Spin Echoes and Gradient Echoes

Immediately after tissue has been excited by an RF pulse and the pulse is turned off, free induction decay be-
gins. To maximize detection of the weak signal, the energy of the relaxing protons is refocused in one of two ways. In spin-echo (SE) techniques, a second RF pulse is applied to the tissue after a short delay (TE) with the proper frequency and magnitude needed to reverse the direction of the protons, so that a new coherent signal (i.e., SE) is produced. In the second method, gradient-echo imaging (GRE), the magnetic field gradients are rapidly switched relative to the main magnetic field to produce a refocused coherent signal.

All magnetic resonance pulse sequences use a combination of magnetic field gradients, RF pulses, and either refocusing RF pulses or refocusing gradients. The science and art of MRI is in creating the order and timing in which RF pulses and gradients are applied to produce the various pulse sequences. Different manufacturers use different acronyms for similar techniques. The most common acronyms are listed in Table 2.

### Contrast: T1 and T2 Relaxation

Different tissues and fluids in the human body have unique proton concentrations and biochemical composition and, thus, behave differently when subjected to MRI techniques. Proton concentration, T1 relaxation rate, and T2 relaxation rate are determinants of signal intensity. Tissue protons lose energy via T1 relaxation and T2 relaxation, which are determined by the tissue type as well as the physiologic or pathologic state of the tissue.

T1 and T2 are intrinsic properties of the proton molecular environment in tissue or fluid. T1 refers to the rate at which protons return to their lowest energy state in the magnetic field after the application of a radiofrequency pulse. T2: the time that the stimulated protons spin coherently after refocusing T2*: the loss of coherent signal when a GRE sequence is used; shorter than T2.

#### Table 1

**Magnetic Resonance Imaging Terminology**

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<td>SPGR: spoiled GRASS, used to reduce T2 contrast and reveal the proton density or T1 contrast between tissues</td>
<td>SSFP: steady-state free precession</td>
<td>STIR: short tau inversion recovery</td>
<td>T1: the rate at which protons return to their lowest energy state in the magnetic field after the application of a radiofrequency pulse</td>
<td>T2: the time that the stimulated protons spin coherently after refocusing</td>
<td>T2*: the loss of coherent signal when a GRE sequence is used; shorter than T2.</td>
<td>TE: short delay prior to application of a second radiofrequency pulse</td>
<td>TR: interval at which radiofrequency pulses are repeated</td>
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#### Table 2

**Commercial Names for Gradient-echo Imaging Sequences**

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<tr>
<th>Manufacturer</th>
<th>Original Sequence</th>
<th>Modified for Greater Speed</th>
<th>Free Induction Decay</th>
<th>Focused Echo</th>
<th>Balanced Steady-state Free Precession</th>
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<tr>
<td>Philips</td>
<td>T1-FFE: T1-weighted Fast Field Echo</td>
<td>TFE: Turbo Field Echo</td>
<td>FFE: Fast Field Echo</td>
<td>T2-FFE: T2-weighted Fast Field Echo</td>
<td>b-FFE: Balanced Fast Field Echo</td>
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expressed in milliseconds; a TR of 500
is 0.5 seconds.) The stimulation pulse is reapplied at a time when tissues have partially relaxed (TR 400 to 750 msec); thus, image contrast is produced between tissues with different T1 relaxation times. Water protons have a relatively long T1 and do not relax as fast as do tissue protons. In T1-weighted sequences, fat is bright and water dark because the fat protons relax to their initial state faster (short T1) and emit more energy than do water protons during the pulse sequence timing.

T2 refers to the time that the stimulated protons spin coherently (ie, remain aligned with the original magnetic frequency) after refocusing. The more complex the physical and chemical environment, the faster the resonant protons lose their coherence, and the shorter the T2 relaxation time. Areas of high water concentration have a longer T2 relaxation time than do other tissues. In T2-weighted images, the signal from CSF is stronger than that from muscle, bone marrow, or spinal cord tissue. In T2-weighted sequences, the 90° and refocusing pulses are spaced farther apart (longer TE) to allow tissues with fast T2 relaxation times to lose coherence, while those with more water maintain more coherence. The repetition time is also long (TR > 1,000 ms) to allow for T1 relaxation to occur in all tissues and liquids. In T2-weighted sequences, tissues with greater water content (eg, edema) have greater signal intensity.

Although the signal in MRI is determined by the concentration of protons and environment, the signal-to-noise ratio is determined by multiple factors, including the sample size, the T1 and T2 relaxation factors, and the number of averages or excitations (NEX). The time of an MRI scan is a function of the number of phase-encoding steps multiplied by TR and NEX. The sample size (ie, in-plane resolution) is determined by the field of view and the matrix size. Magnetic field strength is an important factor in achieving a high signal-to-noise ratio and contrast. The proton energy is approximately nine times greater at 3.0 T than at 1.5 T. Open MRI architecture facilitates dynamic spine imaging, although spatial resolution may be reduced.¹

**Spin-echo Sequence**

The basic SE sequence is the repetitive use of the 90° excitation pulse along with a refocusing pulse. The amount of time allowed the excited spins to relax (TR) and the length of time between the excitation and refocusing pulse (TE) determine whether a sequence is T1-weighted (short TE, short TR) or T2-weighted (long TR, long TE). A faster version of SE, fast spin-echo (FSE),⁴ employs a train of refocusing pulses, usually from 8 to 16 pulses, with gradients applied during each echo within the TR.

The spine is challenging to image, particularly postoperatively, because of unequal changes and the possible presence of metallic devices in the area of interest. Metal creates artifact for both MRI and computed tomography (CT). Recently, new FSE sequences and three-dimensional techniques such as FSE-XETA (extended echo train acquisition)⁵ have been developed that employ flip angle modulation during the FSE readout and echo trains up to 200 echoes long, but with a minimum of echo spacing. The advantage of high-resolution three-dimensional volumes is that multplanar images are acquired much more efficiently than by separate acquisition. Standard SE sequences have the least artifact when metal is present.

**Gradient-echo Sequences**

GRE sequences use rapid changes in the magnetic gradient to create echoes after administration of the excitation pulse. Creating echoes with magnetic gradients is faster than with the use of RF pulses, and GRE imaging has shorter acquisition times than do SE and FSE imaging. However, GRE imaging is highly susceptible to the effects of inhomogeneity in the local magnetic field. The iron in blood products, metallic devices, and surgical devices can cause relatively large local magnetic field inhomogeneities. In the vicinity of ferromagnetic substances, protons in random motion experience rapidly changing magnetic fields and, therefore, interact differently.

When a GRE sequence is used, the loss of coherent signal is referred to as T2*, which is shorter than T2. Blood products are more conspicuous in GRE than in SE sequences. At the interfaces between bone and soft tissue or air, local magnetic fields are inhomogeneous, as are the interfaces between tissue and screws or metallic devices that are implanted in the spine. In these regions, signal decays more rapidly with GRE than with SE sequences.⁶

GRE sequences may also be used to obtain T1 contrast. In one method (spoiled gradient recall acquisition using steady states [SPGR]), RF “spoiler” pulses are used to reduce T2 contrast and reveal the proton density or T1 contrast between tissues.⁷ Another GRE method, the steady-state free precession (SSFP),⁸ employs a string of rapidly applied RF pulses to reinforce the fresh orthogonal magnetization generated at each RF pulse. The SSFP pulse sequence has a signal dependence on the ratio of T2 to T1 relaxation rates and produces images that appear predominantly T2-weighted. These pulse sequences permit short acquisition times (eg, 6 seconds) and real-time screening examinations.

**Inversion Recovery Sequences**

Inversion recovery sequences use a 180° pulse (ie, inversion pulse) to re-
align protons and a second stimulation pulse when tissue protons have partly relaxed.\textsuperscript{9} Contrast is achieved because fat, muscle, soft tissues, and water all have different amounts of magnetization remaining after the 180° pulse when the second pulse is administered. In fluid-attenuated inversion recovery (FLAIR), the signal from water is suppressed, while the signal from tissues persists, in proportion to the T2 relaxation time. In short tau inversion recovery (STIR), the second pulse is administered at a very short time (tau) after the inversion pulse. The signal intensity of fat is suppressed in STIR, which improves the conspicuousness of bone marrow lesions.\textsuperscript{10,11} The strength of FLAIR and STIR sequences is that water protons in edematous tissue, resulting from trauma or other pathology, can be more readily visualized.\textsuperscript{12}

Contrast Enhancement

A gadolinium-containing contrast medium that penetrates the disrupted blood/brain and blood/spinal cord barrier can be used to improve image contrast in inflammatory, infectious, or malignant processes as well as in hypervascular lesions. In the postoperative spine, contrast enhancement is used to distinguish scar tissue, which enhances on MRI scans, from fragments of disk tissue in the epidural space that, lacking capillaries, do not enhance. In the patient with spinal infection, contrast medium administration shows enhancement in affected vertebral bodies and abscesses. Spinal tumors usually show contrast enhancement.\textsuperscript{13} However, gadolinium-enhancing agents, which were once thought to be extremely safe, have been associated with an apparently small but serious risk of nephrogenic systemic fibrosis in patients with severely compromised kidney function. In May 2007, the US Food and Drug Administration issued an updated safety advisory regarding gadolinium-based contrast agents.\textsuperscript{14}

Spinal Application of Newer MRI Sequences

Numerous published reports have documented the poor specificity of MRI in the diagnosis of back pain,\textsuperscript{15} and researchers are developing new magnetic resonance techniques to provide more clinically valuable information.\textsuperscript{16} Diffusion-weighted imaging, which has been effectively used to detect infarction and characterize epidermoid tumors and abscesses in the head, can be used to detect the same conditions in the spine.\textsuperscript{17,18} Because diffusion is affected by the water content and matrix structure, diffusion-weighted imaging may have a role in detecting early degenerative changes in the disk matrix. Changes in the glycosaminoglycans in the disk alter the diffusion patterns of water.

Because the assessment of signal intensity on MRI scans is subjective and is affected by the way in which the image is acquired, more objective and quantitative techniques have been developed. One technique for measuring disk hydration involves calculating T2 relaxation times from an acquisition with multiple echoes at different TEs. Because the T2 relaxation time is an intrinsic property of tissue and is related to the water content, longitudinal changes in disk matrix can be detected with measurements of T2.\textsuperscript{19} T2 measurements are under evaluation as a means of monitoring decreased hydration secondary to degeneration and increased hydration secondary to both proven and experimental therapeutic spine procedures.\textsuperscript{20}

Dynamic imaging of the spine with CT or MRI allows the detection of changes in the neural foramen or spinal canal secondary to physiologic motions.\textsuperscript{21} This imaging may demonstrate foraminal or spinal stenosis that is present only when a load or torque is applied to the spine. Dynamic imaging may be used the way roentgen stereophotogrammetric analysis is used to measure changes in vertebral alignment resulting from a change in the position of the torso.\textsuperscript{22,23} Its potential role in the evaluation of suspected degenerative spinal instability is under investigation.

Magnetic resonance spectroscopy performed with a clinical magnetic resonance imager has been used to measure abnormal collections of metabolites in some spinal disorders.\textsuperscript{24,25} New functional MRI techniques are being explored to evaluate dermatomes and nerve damage of the spinal cord.\textsuperscript{26}

Applications of MRI for Diagnosis of Spine Pathology

Intervertebral Disk and Facet Joint Degeneration

T1-, T2-, and STIR-weighted sagittal MRI scans and axial T1- and T2-weighted images are used to detect suspected degenerative disk disease. For the cervical spine, T2*-weighted images are often substituted for T2-weighted images to reduce artifacts resulting from CSF flow.

MRI scans effectively demonstrate disk structure. T2-weighted images provide good contrast between the peripheral anulus fibrosus, which has low signal intensity, and the cartilage in the inner anulus and the nucleus pulposus, both of which normally have higher signal intensity because of glycosaminoglycans and water in the matrix (Figure 1). Tissue contrast is less visible in FSE than in SE images of the spine. Adult lumbar disks also have a region of lower signal intensity in the central portion of the disk because of the higher fiber content of the region. Although no cleft is present, this region is sometimes called the intranuclear cleft.\textsuperscript{27}

In the patient with disk degeneration, T2-weighted images show decreased signal from the inner anulus fibrosus and nucleus pulposus because of the loss of glycosaminoglycans and water in the matrix.
In degenerating disks, T2-weighted images can also show a linear region of higher signal intensity in the outer anulus, the so-called high-intensity zone (Figure 2). MRI scans do not demonstrate peripheral tears in all degenerating disks but do demonstrate decreased signal intensity in essentially all disks with a radial tear. Diskography demonstrates leakage of contrast medium through radial tears of the anulus fibrosus in all disks with diminished T2 signal intensity, regardless whether the high-intensity zone is evident on imaging. Contrast medium is generally not required for the evaluation of degenerative changes in the disk and facet joints. When used, contrast enhancement may demonstrate granulation tissue that invades disks with a radial tear. In patients with previous laminectomy who have recurrent pain, contrast medium is typically used in an attempt to distinguish recurrent herniated disk fragments, which have little enhancement, from epidural fibrosis, which enhances perceptibly.

The osseous vertebral end plates have low signal intensity because of the very short relaxation time of bone. The Modic classification describes the T1 and T2 signal characteristics of the vertebral end plates associated with intervertebral disk degeneration. Type 1 changes, which are hyperintense in T2-weighted sequences, are assumed to indicate inflammation. Type 2 changes, which are hyperintense in T1-weighted sequences and variable in T2-weighted sequences, depending on the actual sequence chosen, are thought to manifest a more stable and chronic process, resulting in fatty degeneration of the adjacent bone marrow. Type 3 lesions, which are hypointense both in T1- and T2-weighted sequences, are thought to correlate with subchondral bone sclerosis.

In the neural foramen and central spinal canal, T1-weighted images show excellent contrast between fat and the dural sac and root sleeves.
Bone also has low signal intensity on T1-weighted images. Because of its high degree of spatial resolution and contrast with fat, a T1-weighted image shows well the anatomy of the facet joints, ligamentum flavum, and neural foramina and nerve roots.

The amount of disk bulging and disk collapse is usually evaluated based on T1-weighted images. Historically, the nomenclature for describing disk degenerative changes has been controversial. Recently, neuroradiologists and orthopaedic surgeons have attempted to develop a classification system for degenerative disk changes. Generalized displacement of the anulus fibrosus is distinguished from focal disk displacement of the disk margin, which suggests herniation of the nucleus pulposus. Radiculopathy caused by nerve root compression can usually be addressed by examining the axial and sagittal T1-weighted images. In the absence of nerve root compression, a radial tear of the anulus fibrosus may produce back pain or pain radiating into a lower extremity that resembles radiculopathy.

**Spinal Canal Stenosis**

The effect of degenerating disks and facet joints on the central spinal canal can be evaluated effectively with MRI scans, although published studies suggest generally poor evaluator agreement. In the patient with degenerative spondylolisthesis, central spinal stenosis is usually evident in sagittal T1-weighted MRI scans at the L4-5 level, and advanced facet joint degeneration is seen in axial T1-weighted images. Degenerative spondylolisthesis tends to be under-reported.

Several attempts at quantitation and standardization of grading of central canal stenosis have been proposed, but they have not been shown to be superior to inspection of MRI scans. Furlan et al advocate the measurement of maximum canal compromise and maximum spinal cord compression. Maximum spinal cord compression correlated most significantly with poor outcome. T2-, T2*- , and T1-weighted images provide some basis for prognostication in the evaluation of spinal cord hemorrhage and edema.

**Suspected Diskitis/Osteomyelitis**

Diskitis and osteomyelitis produce characteristic changes in spine MRI scans. On sagittal T2-weighted images, disk infection is seen as an increase in signal intensity as cartilage is destroyed. Osteomyelitis appears as an increase in T2 signal intensity of the vertebral marrow as it is invaded with granulation tissue (Figure 3). Increased signal intensity in a vertebra is not specific for osteo-

![Figure 3](image-url)

Sagittal T2-weighted image (A), sagittal T1-weighted image (B), and contrast-enhanced sagittal T1-weighted image (C) in a patient with diskitis, osteomyelitis, and epidural abscess. In panel A, the C5-6 intervertebral disk has high signal intensity. The adjacent C5 end plate is extensively destroyed. The abscess in the epidural space behind C2 can be seen because of the diminished signal intensity compared with the cerebrospinal fluid and because of the displacement of the spinal cord posteriorly. In panel C, the capsule of the abscess at C2 through C4 (upper arrow) and the phlegmon at C5 (lower arrow) are evident. The C5-6 disk and the C5 and C6 vertebrae enhance markedly.
myelitis because it may appear adjacent to disks with degenerative changes. In the patient with suspected diskitis or osteomyelitis, the appearance of the disk, end plates, epidural space, and paraspinal tissues must be evaluated carefully.

Contrast medium is often administered to detect inflammation in a disk or vertebra and to detect enhancement surrounding epidural or paraspinal abscess cavities. The use of the fat-suppression pulse aids in distinguishing the abnormal enhancement from fat normally present in the spine. The changes of diskitis and osteomyelitis demonstrated by MRI scans in the spine lag behind the clinical status of the patient. Clinical deterioration or patient amelioration usually precedes by 2 weeks the changes visible on MRI scans.

**Suspected Spinal Column Neoplasia**

MRI scans effectively demonstrate tumors of the spine whether they are intramedullary, extramedullary, or extradural. An intramedullary tumor is likely best shown on T2-weighted images as a process that enlarges the cord and increases the signal intensity locally. Intramedullary tumors often show contrast enhancement. Tumors on the pial surface of the cord and in the extramedullary compartment may require contrast enhancement for detection. Fat saturation may improve the conspicuousness of tumor and of contrast enhancement when evaluating a patient for tumors in the epidural space or in the vertebral column (Figure 4).

**Vascular Disorders**

MRI has improved the detection of dural arteriovenous fistulas that cause degeneration of the spinal cord. The symptoms of arteriovenous fistulas and the age groups affected are similar to those of spinal stenosis. MRI scans demonstrate edema in the spinal cord that results from venous stasis and often demonstrate the irregular pattern of abnormal veins on the surface of the spinal cord (Figure 5). T1-weighted contrast-enhanced images may demonstrate enhancement of dural arteriovenous fistulas in the distal cord and in the engorged veins. Abnormal vessels can also be detected, and the site of the arteriovenous malformation can be localized by the use of spinal magnetic resonance angiography.

**Trauma**

Damage to the spinal cord and ligaments are optimally demonstrated
Demyelinating Disease

Demyelinating spinal cord plaques can be the initial presentation of multiple sclerosis (MS). FLAIR and STIR are the most sensitive sequences for detecting T2-signal abnormalities in the spinal cord. Plaques most often occur in the dorsolateral cord. Acutely, plaques may enhance and have mass effect. However, as in the brain, not all white matter changes are the result of MS plaques, and clinical history and laboratory correlation are necessary. New techniques of diffusion-weighted imaging, diffusion tensor tractography, and magnetic resonance spectroscopy are being explored to evaluate chronic and acute spinal cord damage caused by MS.40,41

Summary

MRI is ideally suited for evaluation of the intervertebral disk spaces, bone marrow, the CSF space, spinal canal, and soft tissues. However, this modality should not be used in patients with pacemakers, nerve stimulators, ferromagnetic foreign bodies in the eyes, or in those who suffer from claustrophobia. CT, especially high-resolution helical scanning, is superior for generating images of osseous structures.

References

Evidence-based Medicine: There are several level I/II prospective studies (references 3-7, 10, 13, 15, 21, 23, 28, 33-37, 40, and 41). Level III case-control studies include references 1, 2, 8, 11, 12, 14, 16-19, 22, 24-27, 29-32, 38, and 39.

Citation numbers printed in bold type indicate references published within the past 5 years.
