MRI Techniques: A Review and Update for the Orthopaedic Surgeon

Abstract

MRI plays a critical role in all orthopaedic practices. A basic working knowledge of the most commonly used pulse sequences in musculoskeletal imaging and the appearance of normal tissues on those sequences is critical to confident MRI interpretation. The orthopaedic surgeon should be familiar with appropriate use of intravenous and intra-articular contrast and its limitations. Concepts key to MRI interpretation include image contrast and resolution, signal, noise, and pulse sequence. Recent advances in anatomic and functional imaging highlight the robust potential of MRI for musculoskeletal evaluation. As MRI technology evolves, the orthopaedic surgeon must stay current on these technologic advances to use this tool to its fullest potential.

Modern high field strength MRI uses superconducting magnets and radiofrequency (RF) coils to manipulate hydrogen protons, creating a detailed, high-contrast image. A powerful magnet, optimally one with a field strength of 1.5 to 3.0 tesla (T), is used to synchronize the nuclear motion of water protons in the interrogated tissue. Once protons are aligned in the main magnetic field, they are primed to absorb energy added to the system by an RF pulse. When the pulse is turned off, tissues release the absorbed energy at different rates, which determines their T1 and T2 times. The T1 time constant refers to the time it takes for protons to realign themselves with the magnetic field. T2 refers to the time it takes for protons spinning in a synchronized fashion to lose their coherence. An RF receiver or coil is used to detect the emitted energy, termed “signal,” from the recovering protons as they return to equilibrium in the main magnetic field. Smaller gradient magnets are used to acquire spatial information.

Patient Screening

All patients should undergo rigorous screening prior to an MRI examination. Patients should be queried regarding the presence of medical implants; decorative tattoos or permanent cosmetics; prior surgery; prior occupation (ie, welding, metal working) or injury resulting in retained metallic fragments, particularly near or in the eyes; possible pregnancy; and breastfeeding status. In addition, patients who require intravenous (IV) contrast must also be screened for predisposing risk factors for nephrogenic systemic fibrosis (NSF).

The strong magnetic field can damage or dislodge ferrous metallic implants or foreign bodies. If the patient is unsure of the type and manufacturer of his or her implanted
device, deciding to image is at the discretion of the physician responsible for the study. Hazardous devices include aneurysm clips, cardiac pacemakers, implantable cardioverter defibrillators, and electronic implants of uncertain age and type. If documentation regarding such a device is unavailable, MRI should be reconsidered. A list of medical devices and their magnetic resonance risk profile can be found at MRIsafety.com.

Tissue heating may occur during MRI, not just in patients with metal, but also in those with decorative tattoos. Burns have been described in these patients; therefore, a cool compress may be applied to tattoos before MRI examination. Adverse reactions associated with permanent cosmetics are rare; occasionally a tingling sensation is reported. Some image degradation may occur.

In patients with an occupational and/or injury history that places the patient at risk for retained metal fragments near critical anatomic structures, plain radiographs are adequate and recommended for screening. The presence of intraorbital metal is a contraindication to MRI. Currently, no studies report detrimental effects to the growing fetus associated with MRI; however, the literature on this issue is sparse. Current recommendations for the pregnant orthopaedic patient are that MRI not be withheld in the setting of active or acute brain or spine disease, acute chest, abdomen, or pelvic disease not diagnosable with ultrasound, and cancer. IV gadolinium contrast has a plasma half-life of approximately 2 hours and is cleared from the bloodstream in approximately 24 hours. The expected dose absorbed by the infant from breast milk is less than 0.0004% of the intravascular dose given to the mother. Theoretic risks include allergic sensitization or reaction and direct neurotoxicity from any nonchelated gadolinium in breast milk. No data exists to substantiate adverse events to an infant from the tiny amount of gadolinium excreted into breast milk. Currently, it is considered safe to continue breast-feeding after receiving gadolinium; however, after an informed discussion, mothers may refuse gadolinium-based contrast agents (GBCAs) or may choose to pump and discard their breast milk for 24 hours following a contrasted examination.

Aside from dose-dependent nephrotoxicity similar to that associated with iodinated contrast agents used for CT, gadolinium poses an additional risk of NSF, a rare life-threatening disease affecting patients with compromised renal function. NSF primarily involves the skin and subcutaneous tissues but is also known to involve other organs, such as the lungs, esophagus, heart, and skeletal muscles. Patients with acute or chronic severe renal failure are at greatest risk; screening is aimed at identifying patients with a one-time glomerular filtration rate <45 (stage 3B, 4, or 5 renal failure). In those patients, noncontrastted imaging is preferable. If GBCA must be used, the dose should be reduced. Some GBCAs, including gadodiamide, gadopentetate dimeglumine, and gadoversetamide, are specifically contraindicated in patients at risk of NSF. Therefore, an alternate agent should be used in an at-risk patient if contrast is deemed medically necessary. The American College of Radiology (ACR) Contrast Committee recommends prescreening patients before administration of GBCA by reviewing a recent (within the last 6 weeks) glomerular filtration rate in patients with a history of renal disease, including solitary kidney, renal transplant, renal tumor, age >60 years, history of hypertension, diabetes, severe hepatic disease, prior liver transplant, or pending transplant.

**Terminology and Key Concepts**

Image contrast and resolution, signal, noise (ie, background signal), and pulse sequence are key concepts in any review of MRI techniques. In addition to these concepts, the orthopaedic surgeon should be familiar with terminology that primarily pertains to pulse sequences. Whether spin-echo (SE) or fast spin-echo (FSE) technique is applied, musculoskeletal imaging sequences are typically T1-, T2-, or proton density (PD)-weighted (Table 1).

**Fat Suppression**

In some situations, it is advantageous to suppress the signal emanating from fat. This is achieved by one of several methods: frequency-selective fat saturation (FSFS), short time inversion recovery (STIR), Dixon’s method, slice-selective gradient reversal, and magnetization transfer–based techniques. Musculoskeletal imaging typically employs either FSFS or STIR techniques.

FSFS is a technique used with other pulse sequences that involves applying a special gradient to crush the signal emanating from fat. Typically, the technique is used with postgadolinium T1-weighted imaging to highlight areas of enhancement, or, in the case of arthrography, to highlight intra-articular gadolinium. FSFS is also useful to confirm the fatty nature of a mass and to distinguish fat from methemoglobin, both of which appear bright on T1-weighted magnetic resonance images without FSFS.

FSFS has several inherent limitations. Potential inhomogeneous fat suppression is the most problematic limitation because magnetic field inhomogeneities and susceptibility effects result in regions of poor fat suppression. This failure to ade-
quately suppress the signal emanating from fat, or to inadvertently suppress the water signal, typically occurs near the edges of the image and in regions prone to susceptibility artifact; it manifests as fading areas of brightness in characteristic locations (ie, margins of the image, air–soft-tissue interfaces such as those around toes). In addition, when magnets with a lower field strength (<1T) are used, this technique is often not available or is ineffective because the resonant frequencies of fat and water are similar at lower field strength and cannot be easily separated. A saturation pulse is applied before each slice-selective RF pulse. In T2-weighted imaging, the additional time (10 msec) associated with application of the saturation pulse is small compared with acquisition time; however, in fast spin-echo imaging, the saturation time and acquisition time are comparable, resulting in a substantial increase in the imaging time.³

The STIR technique does not suffer from such drawbacks. Instead of exploiting the different resonant frequencies of fat and water, STIR makes use of the different tissue relaxation times. Consequently, fat saturation is more homogeneous, making this technique a better choice in the setting of hardware and for imaging at large tissue-air interfaces. This method is insensitive to magnetic field inhomogeneities, making it ideal for low field strength magnets and for patients with metal implants. Differences in both the inherent T1 and T2 properties of tissue contribute to image contrast. Water, with long T1 and T2 times, appears very bright.⁴ However, because gad
linium and fat have similar relaxation times, they appear dark on STIR sequences. Although many think of FSFS and STIR as interchangeable because the resultant images have a similar appearance, there are important differences.

**Application of Pulse Sequences**

Each tissue type has its own unique, inherent T1 and T2 properties (Tables 2 and 3). The acquired image is a product of those inherent tissue properties and the technique used to capture them. By convention, signal is displayed as varying degrees of brightness. More signal generates a brighter area on the image. Attributes of “bright” and “dark” are most useful when qualified with a relative comparison. In musculoskeletal imaging, that internal reference is skeletal muscle.

### Bone

**Normal**
Given the relative paucity of protons in the calcified matrix, cortical bone appears dark or black on all pulse sequences. Conversely, normal marrow fat is brighter than muscle. Hematopoietic marrow is less bright than fat but should remain brighter than skeletal muscle on non-fat-saturated sequences.

**Pathology**
T1-weighted magnetic resonance images can be used to delineate trabecular architecture and the margins of marrow-replacing lesions or processes like tumor or infection, but marrow edema, unless significant, will be hard to see. STIR and T2-weighted fat-suppressed FSE sequences both depict edema associated with marrow pathology. If images are obtained using a magnet with low field strength (<1T), attempts at FSFS may be ineffective, and STIR sequences will better highlight marrow pathology (Figure 1).

### Ligaments and Tendons

**Normal**
Ligaments and tendons typically appear dark on all sequences. Larger tendons like the Achilles, quadriceps, and patellar tendons may have several normal well-defined linear striations of increased signal intensity. Tendons with a broad insertion, such as the posterior tibial tendon and peroneal longus, may also demonstrate mildly increased signal intensity because they insert on broad interfaces. It is common for some ligaments (eg, anterior cruciate, posterior talofibular, deltoid) to contain several normal striations of increased signal intensity on T1- and T2-weighted sequences. T1-weighted

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**Table 2**

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Tissue Property</th>
<th>Best Sequences</th>
<th>Potential Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>Marrow fat, rigid mineralized cortical matrix</td>
<td>T1 T2-weighted fat-saturated FSE, STIR</td>
<td>T2-weighted FSE without fat-saturation may fail to show significant marrow pathology</td>
</tr>
<tr>
<td>Ligaments and tendons</td>
<td>Organized, dense collagenous architecture</td>
<td>T1 or T2-weighted fat-saturated FSE, STIR</td>
<td>Magic angle artifact on low TE sequences (T1, PD)</td>
</tr>
<tr>
<td>Muscle</td>
<td>Individual fascicles organized into bundles, usually with visible intervening fat</td>
<td>T1 T2-weighted fat-saturated FSE, STIR</td>
<td>Edema and fatty atrophy indistinguishable on non-fat-saturated T2-weighted FSE</td>
</tr>
<tr>
<td>Joint, bursa, synovium</td>
<td>Contain simple fluid</td>
<td>T2-weighted FSE with and without fat saturation STIR, T2-weighted fat-saturated FSE</td>
<td>None</td>
</tr>
<tr>
<td>Fibrocartilage</td>
<td>Organized relatively acellular tissue</td>
<td>PD, T1 PD with and without fat saturation, T1</td>
<td>Susceptible to magic angle artifact, long TE sequences can obscure tears, blurring with T2-weighted FSE</td>
</tr>
<tr>
<td>Articular cartilage</td>
<td>Water in an organized collagen and proteoglycan environment</td>
<td>PD, T2-weighted FSE PD, T2-weighted FSE</td>
<td>Nonuniform signal on GRE may mimic disease</td>
</tr>
</tbody>
</table>

FSE = fast spin-echo, GRE = gradient-recalled echo, PD = proton density, STIR = short time inversion recovery, TE = echo time
MRI is useful for visualizing tendon enlargement and general architecture; however, like other short echo time (TE) sequences (eg, PD, gradient-recalled echo [GRE]), T1-weighted sequences are susceptible to magic angle artifact. This artifact is aberrant increased signal intensity that is seen in highly organized tissues with tightly packed collagen fibers when the fibers are oriented at 55° to the main magnetic field. The use of comparative T2-weighted or STIR sequences facilitates differentiation between true pathology and artifact (Figure 2).

Pathology
Favored sequences for evaluation of tendons and ligaments include PD-weighted, T2-weighted fat-saturated FSE, and STIR sequences. T1-weighted imaging optimizes soft-tissue contrast; however, many practices have replaced this sequence with a similar PD-weighted sequence to better highlight intrasubstance edema associated with acute trauma and increased water content that is seen in chronically traumatized tendons and chondroid metaplasia. Tenosynovitis can also be visualized well on fluid-sensitive sequences.

Table 3
Hallmark Signal and Anatomic Features Associated With Specific Pathology

<table>
<thead>
<tr>
<th>Pathology</th>
<th>Hallmark Signal Features</th>
<th>Anatomic Features</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture</td>
<td>Decreased linear T1 signal in bone, increased T2/STIR signal in bone and regional soft tissues</td>
<td>Deformity, cortical step-offs</td>
<td>NA</td>
</tr>
<tr>
<td>Effusion</td>
<td>Capsular collections with increased T2/STIR signal</td>
<td>Joint capsule distension, communicating bursal distension</td>
<td>NA</td>
</tr>
<tr>
<td>Synovitis</td>
<td>Intermittent/decreased T2 signal with frond-like proliferations typically visible on background contrast of increased T2 signal effusion</td>
<td>Diffuse or mass-like intra-articular soft tissue</td>
<td>IV contrast can help distinguish between vascular synovitis and effusion</td>
</tr>
<tr>
<td>Tenosynovitis</td>
<td>Increased T2 signal distension of tendon sheaths, ± synovitis</td>
<td>Diffuse or mass-like tenosynovial soft tissue</td>
<td>IV contrast may reveal synovitis in the absence of significant tendon sheath fluid</td>
</tr>
<tr>
<td>Fibrocartilage tear (eg, labrum, meniscus)</td>
<td>Increased linear intrasubstance PD signal reaching an articular surface (eg, meniscus)</td>
<td>Meniscal deformity, displaced fragments, irregular surfaces</td>
<td>MRA most sensitive for hip/shoulder labral pathology. Not needed for menisci.</td>
</tr>
<tr>
<td>Muscle injury</td>
<td>Increased feathery T2/STIR signal, increased T2 signal with intramuscular collections, increased T1 signal with intramuscular hematomas, disrupted T2 hypointense fibers on background of edema, increased T1 signal with fatty infiltration (chronic)</td>
<td>Musculotendinous defects, muscle architecture disruption</td>
<td>NA</td>
</tr>
<tr>
<td>Tendinopathy</td>
<td>Increased intrasubstance PD signal that is less than that associated with fluid on T2/STIR</td>
<td>Tendon enlargement, fraying, intrasubstance, linear tears</td>
<td>NA</td>
</tr>
<tr>
<td>Tumor</td>
<td>Varies depending on composition</td>
<td>Mass ± bone or soft-tissue invasion</td>
<td>Not routinely needed. Can reveal tumor recurrence following surgery, cystic versus solid tumor components, better characterization of necrosis.</td>
</tr>
</tbody>
</table>

IV = intravenous, MRA = magnetic resonance arthrography, NA = not applicable, PD = proton density, STIR = short time inversion recovery

Pathology
Favored sequences for evaluation of tendons and ligaments include PD-weighted, T2-weighted fat-saturated FSE, and STIR sequences. T1-weighted imaging optimizes soft-tissue contrast; however, many practices have replaced this sequence with a similar PD-weighted sequence to better highlight intrasubstance edema associated with acute trauma and increased water content that is seen in chronically traumatized tendons and chondroid metaplasia. Tenosynovitis can also be visualized well on fluid-sensitive sequences.

Muscle
Normal
On all sequences, skeletal muscle demonstrates intermediate signal intensity and serves as a relative comparison for signal characterization of adjacent tissues.

Pathology
STIR and T2-weighted sequences highlight muscle edema and fluid collections, whereas T1-weighted MRI is superior for evaluation of fatty and volumetric atrophy. T1-weighted sequences are also useful...
for visualizing intramuscular hematomas and distinguishing subacute blood from edema, both of which appear bright on fluid-sensitive sequences.

**Joint Spaces, Bursae, and Synovium**

**Normal**
Nonpathologic joint fluid appears homogeneously bright on T2-weighted magnetic resonance images and darker than muscle on T1-weighted magnetic resonance images. Normal synovium is typically not seen without gadolinium contrast; however, when present, synovitis appears as diffuse or nodular regions of frond-like thickening associated with joint capsules and recesses. Similarly, bursae are not seen unless they are distended with fluid, in which case they appear as ovoid hyperintense collections on T2-weighted magnetic resonance images and are typically in predictable locations such as overlying the greater trochanter or patellar tendon, beneath the acromion, or behind the medial knee tracking to the interval between the semimembranosus tendon and the tendon of the medial head of the gastrocnemius muscle.

**Pathology**
MRI evaluation of abnormal menisci demonstrates increased intrasubstance signal; it is often seen in conjunction with morphologic abnormalities and is sometimes seen with displaced meniscal fragments. Sequences with longer TE (T2-weighted sequences) are less sensitive for intrasubstance pathology, and T2-weighted FSE magnetic resonance images may have blurring that can obscure tears (Figure 3). However, when evaluating the meniscus postoperatively, T2 signal characteristics play an important role in differentiating meniscal healing from scarring and repeat tear.

**Fibrocartilage**

**Normal**
This highly organized collagenous tissue typically appears dark on all MRI sequences. Short TE sequences are preferred for detection of pathology; in modern practice, PD-weighted sequences have largely replaced T1-weighted sequences for detection of both meniscal and labral tears. PD-weighted sequences can also be used for reliable evaluation of articular cartilage, allowing for a reduction in the overall number of sequences required per study.

**Pathology**
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**Hyaline Cartilage**

**Normal**
Depending on sequence, the appearance of articular cartilage varies. On
PD, STIR, T1-weighted, and T2-weighted FSE sequences, articular cartilage is of intermediate brightness. Fluid-sensitive sequences capitalize on the joint fluid to highlight the articular surface. In addition, STIR and fat-saturated T2-weighted imaging show underlying marrow changes that accompany more severe cartilage loss.

The GRE sequence has long been touted for its ability to show articular cartilage as a very bright structure that is clearly separate from subchondral bone and adjacent joint fluid. Although changes in overall cartilage thickness can be seen, subtle changes in internal signal are not visible. Underlying marrow change may be obscured.

**Pathology**

Cartilage abnormalities range from subtle changes in signal to gross morphologic abnormalities, including fibrillation, fissuring, flap formation, delamination, and displaced fragments. In the past decade, studies have consistently shown that PD-weighted and fat-suppressed PD-weighted sequences are comparable to GRE, T2-weighted FSE, and STIR sequences in terms of demonstrating abnormalities. Most centers rely on PD-weighted sequences for evaluation of articular cartilage because they best illustrate both the surface and internal architecture of the articular cartilage.

Imaging performed with 1.5- and 3-T magnets can resolve partial-thickness cartilage loss and fissures (Figure 4). Even magnetic resonance images obtained at low field strength can delineate areas of full-thickness cartilage loss, especially if PD-weighted sequences are viewed in conjunction with highly fluid-sensitive STIR sequences.

That being said, optimal imaging of articular cartilage is performed with at least 1.5 T units. Low field strength units may not be able to resolve clinically significant abnormalities. Although 3-T systems have the potential to generate magnetic resonance images with higher signal-to-noise and contrast-to-noise ratios than 1.5-T systems, studies have shown that no difference exists between the two systems in terms of measurement of cartilage thickness.

**Contrast Agents**

Musculoskeletal MRI does not routinely require the use of IV or intra-articular contrast agents. The most common indications for IV contrast include postoperative imaging of the spine, infection, and postoperative evaluation of musculoskeletal tumors. Intra-articular contrast can aid in visualization of ligaments and fibrocartilage (e.g., MRA).

In postoperative imaging of the spine, contrast-enhanced MRI is an effective way to differentiate avascular herniated disk material from highly vascular epidural fibrosis in patients with recurrent pain following surgery.

For evaluation of bone and soft-tissue tumors, use of contrast-enhanced MRI should be limited to answering specific clinical questions. In a study of 242 patients with suspected primary musculoskeletal neoplasm, contrast-enhanced MRI did not contribute to differential diagnosis or patient management in 89% of patients. However, it was helpful in...
guiding biopsy of bulky lesions because it allowed differentiation of the cystic/necrotic areas from solid components. Contrast-enhanced MRI also aids in evaluation of treated tumor beds for possible recurrence. In patients with inflammatory arthritis, contrast helps to differentiate between pannus formation and joint fluid, which is difficult to distinguish on noncontrast magnetic resonance images.\(^\text{17}\) In evaluation of patients with infection, contrast may improve detection of abscesses and identification of small sinus tracts.\(^\text{18}\)

### Clinical Application

An awareness of the strengths and weaknesses of each pulse sequence (Table 4) allows for the creation of standard protocols which can be efficiently applied to common clinical scenarios. Routine protocols are devised to highlight tissues of interest (ie, the rotator cuff and labrum in the shoulder, menisci and articular cartilage in the knee) and characterize common pathology (Table 3).

### Tumor and Infection

Typically, tumor and infection protocols are similar. T1-weighted imaging makes use of the inherent contrast between marrow fat (high intensity signal) and marrow-replacing processes (lower intensity signal) to highlight masses or focal infection. In the proper clinical setting (ie, physical examination or laboratory findings suggesting infection) confluent replacement of normal marrow fat visible on T1-weighted MRI has been shown to be up to 95% sensitive and 91% specific for diagnosis of osteomyelitis of the foot.\(^\text{19}\)

A fluid-sensitive sequence will highlight areas of pathology accompanied by edema, but this is less specific than marrow replacement when evaluating for infection.\(^\text{20}\) However, in cases of nonsclerotic bone neoplasm, T2-weighted fat-saturated FSE or STIR sequences may highlight small abnormalities that are inconspicuous on T1-weighted magnetic resonance images. T2-weighted MRI has been shown to be comparable to contrast-enhanced T1-weighted imaging for de novo evaluation of bone

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**Sagittal proton density (PD)-weighted fast spin-echo (A) and T2-weighted fat-saturated fast spin-echo (B) magnetic resonance images of the knee demonstrating a full-thickness defect of the hyaline cartilage over the posterior tibial plateau with a free cartilage fragment (arrow). Notice the superior resolution of the PD-weighted magnetic resonance image. In addition to the defect and the fragment, partial-thickness loss of adjacent femoral articular cartilage was detected.**

**Figure 4**

**Sagittal proton density (PD)-weighted fast spin-echo (A) and gradient echo (B) magnetic resonance images of the knee in a patient with a meniscal tear. An intrasubstance meniscal signal (arrow) is visible on the PD-weighted magnetic resonance image but not on the T2-weighted magnetic resonance image. An oblique flap tear of the posterior horn of the medial meniscus manifests as linear increased signal that extends to the inferior articular surface.**

**Figure 3**
and soft-tissue tumor margins, neurovascular invasion, and joint involvement associated with bone and soft-tissue tumors16 (Figure 5). Joint and neurovascular involvement is best assessed on T1-weighted sequences without fat suppression because the intervening fat planes may be blurred on STIR, T2-weighted, and postgadolinium fat-saturated T1-weighted sequences.21

Although contrast is not routinely required in the setting of infection and preoperative tumor evaluation, it is advised in some instances. In potential cases of osteomyelitis, abscess or sinus tract formation can be difficult to delineate with noncontrast imaging alone. Contrast is also helpful for early detection of tumor recurrence in the setting of posttreatment oncology follow-up.

**Trauma and Sport-related Injuries**

Imaging studies are selected based on the patient’s history and clinical examination findings. Imaging guidelines exist for several clinical scenarios. For example, the American Academy of Orthopaedic Surgeons has clinical practice guidelines that address the role of imaging in the diagnosis and treatment of osteochondritis dissecans.22 In addition, the American Academy of Orthopaedic Surgeons is developing appropriate use criteria for treatment of the rotator cuff and nonsurgical treatment of osteoarthritis of the knee.23

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**Table 4**

<table>
<thead>
<tr>
<th>Pulse Sequence</th>
<th>Strength</th>
<th>Drawback</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1-weighted SE/FSE</td>
<td>Marrow pathology; evaluation of fat, protein, and blood; good anatomic detail; postgadolinium with fat saturation for arthrography and tumor/infection protocols; muscle atrophy</td>
<td>Edema, magic angle artifact</td>
</tr>
<tr>
<td>T2-weighted SE</td>
<td>Marrow and soft-tissue pathology, fluid collections</td>
<td>Time-consuming</td>
</tr>
<tr>
<td>T2-weighted FSE</td>
<td>Faster than T2-weighted SE, marrow and soft-tissue pathology, fluid collections</td>
<td>Blurring, fat saturation needed to detect marrow pathology</td>
</tr>
<tr>
<td>Proton density-weighted SE/FSE</td>
<td>Hyaline and fibrocartilage, anatomy, metal implants</td>
<td>Magic angle artifact, reduced sensitivity for edema and marrow pathology</td>
</tr>
<tr>
<td>STIR</td>
<td>Edema and marrow pathology, fluid collection, metal implants</td>
<td>Less detail</td>
</tr>
<tr>
<td>T2-weighted GRE</td>
<td>Articular cartilage thickness, hemosiderin deposition, chondrocalcinosis, loose osseous bodies, potential for very thin slices without signal loss</td>
<td>Metal implants, marrow pathology</td>
</tr>
</tbody>
</table>

FSE = fast spin-echo, GRE = gradient-recalled echo, SE = spin-echo, STIR = short time inversion recovery.

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**Figure 5**

Coronal T1-weighted spin-echo (A) and postcontrast T1-weighted fat-saturated (B) magnetic resonance images of the lower extremities in a patient with osteosarcoma complicated by pathologic fracture. A, The T1-weighted spin-echo sequence clearly delineates neoplastic diaphyseal marrow replacement and the inferior margin of tumor (arrow). B, The postcontrast magnetic resonance image is somewhat misleading because only the inferior margin of the tumor (arrow) enhances. On gross section, the entire distal femoral diaphysis was involved.
has published imaging recommendations for evaluation of acute shoulder pain, acute knee trauma, nontraumatic knee pain, and chronic hip pain as part of the ACR Appropriateness Criteria. However, no standardized recommendations exist for obtaining repeat magnetic resonance images in the absence of intervening surgery or history of cancer. In two retrospective reviews, the authors concluded that repeat shoulder and knee MRI may have clinical merit. Although these reviews had significant limitations, they highlight the need for further investigation to determine the indications for and the cost-effectiveness and efficacy of repeat MRI examination of these joints. At our institution, the total cost of MRI without contrast is $2,800 and $2,630 for shoulder and knee magnetic resonance images, respectively, with the technical fee comprising 89% of the total cost.

Knee
Routine evaluation of the knee typically includes axial and coronal fatsuppressed PD-weighted sequences, sagittal PD- and T2-weighted sequences, and, occasionally, a sagittal FSE three-dimensional GRE sequence. The PD-weighted sequence is used to identify meniscal tears and articular cartilage abnormalities. The T2-weighted sequence highlights marrow abnormalities, provides a high-contrast evaluation of the extensor mechanism, allows for reassessment of the anterior cruciate and posterior cruciate ligaments, and is critical for postoperative evaluation of the meniscus. T2-weighted MRI provides increased specificity for assessment of tendinous or ligamentous pathology because magic angle artifact does not occur on this sequence. The GRE sequence is used to evaluate the thickness of hyaline cartilage and to identify small ossified intra-articular bodies, areas of blooming in the setting of pigmented villonodular synovitis, and chondrocalcinosis, which may be more conspicuous on this sequence given the contrast between the bright articular cartilage and darker calcium.

Typically, the standard sports knee protocol is not changed for postoperative evaluation of the meniscus, but greater emphasis is placed on T2-weighted fat-saturated FSE sequences. On T1- and PD-weighted sequences, intact fibrocartilaginous repairs may show increased intrasubstance “signal conversion,” or persistent change from normal dark fibrocartilage to fibrocartilage that has brighter intrinsic signal, which may mimic a repeat tear and can persist for 12 or more years following surgery. Using the well-accepted criteria of displaced meniscal fragment and/or linear T2 hyperintense fibrocartilaginous cleft, conventional MRI has been shown to reliably detect repeat meniscal tears. In this setting, the benefit of direct MRA is controversial. Although many studies have reported increased accuracy for detection of recurrent tears with this method, some have shown that the benefits of direct MRA are limited to a small number of patients.

Shoulder
Typical sequences for routine shoulder imaging include axial, oblique coronal, and oblique sagittal fatsuppressed PD-weighted sequences, oblique coronal T2-weighted FSE sequences, and, on sequences in which fat saturation can be suboptimal with low field strength magnets, oblique coronal and oblique sagittal STIR sequences. Fluid-sensitive sequences are used to identify marrow abnormalities, to confirm and further define tendon abnormalities visible on PD-weighted magnetic resonance images, and to visualize bursal distension and joint effusion. The fibrocartilaginous labrum is evaluated on PD-weighted sequences, and the cuff is best evaluated on PD- and T2-weighted STIR sequences. Muscle atrophy is assessed on PD-weighted magnetic resonance images, whereas muscle edema is best seen on T2-weighted and STIR sequences.

Hip
Conventional MRI has >90% sensitivity for diagnosis of fibrocartilaginous meniscal tears; however, MRA with a small field of view (ie, size of the frame in mm² or cm² that defines the imaged region) provides the most accuracy in diagnosis of labral tears in the hip and shoulder. Hip protocols include fat-saturated PD-weighted or T1-weighted MRI (for arthrography) in various planes and fluid-sensitive imaging in at least one plane to assess regional soft tissues and better highlight subtle but symptomatic marrow abnormalities (Figure 6).

New Advances
Recent advances in musculoskeletal MRI have yielded new techniques and new applications of proven techniques that serve to enhance the orthopaedic surgeon’s ability to assess the musculoskeletal system. These techniques and applications have allowed improved assessment of the tissue surrounding implants and have provided novel ways to quantify articular cartilage and investigate musculoskeletal structure and function.

Metal artifact reduction sequences are an example of one technologic advancement. The magnetic susceptibility of metal implants and the surrounding tissues differ greatly, creating artifact and resulting in signal misregistration. The consequent magnetic resonance image contains regions of both signal dropout and
erroneous high-intensity signal that obscures tissues adjacent to the implant. Also, techniques such as fat suppression are impaired because they require a homogeneous main magnetic field to be effective. Historically, this problem has limited the use of MRI in many trauma, arthritic, and oncology patients. Traditional approaches to this issue include the use of SE rather than FSE, STIR sequences as opposed to frequency-selective methods for fat suppression, high frequency-encoded bandwidths, and very thin slices or, when possible, the use of non–slice-selective pulses. Newer and less used techniques include ultra-short TE imaging, improved view angle tilting methods to reduce blurring through slices, and multispectral imaging methods such as multiacquisition variable-resonance image combination and slice encoding for metal artifact correction in MRI. Clinically, these techniques improve the surgeon’s ability to evaluate the bone and soft tissues surrounding an arthroplasty implant or nail to assess a tumor, pseudotumor, or infection (Figure 7).

Several studies have reported on novel ways to assess the structure, biochemistry, and physiology of articular hyaline cartilage. Three-dimensional FSE, steady-state free precession, driven equilibrium Fourier transform, GRE imaging, and double-echo steady-state imaging are options for characterizing cartilage structure. Biochemistry and physiology are now being investigated with T2 mapping and, more recently, with mapping of the time constant T1 in an effort to characterize macromolecule-water exchange. Sodium imaging and delayed gadolinium-enhanced MRI of cartilage have been used to characterize sodium content and fixed charge density, respectively. Finally, chemical exchange saturation transfer imaging, which is sensitive to macromolecule-water exchange, has also been proposed as a method for imaging glycosaminoglycan content. Diffusion-weighted imaging, a proven technique in neuroimaging, is now applied in the musculoskeletal setting. This technique provides functional information about movement of water at the cellular level. New musculoskeletal applications include evaluation of vertebral frac-
tures, bone marrow malignancy, osseous infection, primary soft-tissue tumors, and posttherapy tumor follow-up. The ability to distinguish between benign and malignant vertebral body fractures and posttherapy tumor assessment are the most promising advances associated with these new applications.45

Finally, advances in the characterization of skeletal muscle physiology and pathology have recently been achieved using MRI. For example, T2 mapping and/or measurement of water diffusion have been shown to be sensitive to muscle damage processes, like those following muscle strain46 and experimental induction of muscle damage.47-49 In models of muscular dystrophy, diffusion tensor imaging-based fiber tracking has successfully been applied to skeletal imaging-based fiber tracking has successfully been applied to skeletal muscle to quantify normal muscle architecture50,51 and the alterations to muscle architecture associated with lateral patellar dislocation.52 Improved characterization of muscle function has been achieved with the application of contrast dependent on blood oxygenation level. This technique has yielded useful information regarding muscle microvascular function in obese and diabetic subjects53 as well as muscle deformation patterns at the myotendinous junction associated with hamstring strain.53

**References**

**Evidence-based Medicine:** Levels of evidence are described in the table of contents. In this article, references 48, 49, and 51-53 are level I studies. References 6-9, 14, 15, 27, 30, 33, 39, 41, 44, 46, 47, and 50 are level II studies. References 10, 11, 13, 17, 25, 26, 28-32, and 34-36 are level III studies. References 18, 19, 21, and 37 are level IV studies. References 3-5, 12, 16, 20, 38, 40, 42, and 45 are level V expert opinion.

References printed in bold type are those published within the past 5 years.


**Summary**

Although the physics supporting MRI are complex and the associated terminology may be overwhelming, most MRI studies can be accurately reviewed with a working knowledge of the strengths and weaknesses of the most commonly used pulse sequences. Although intravenous gadolinium-based contrast agents are often not required for musculoskeletal applications, they are useful in certain situations and should be ordered with awareness of the patient’s other medical conditions, particularly those pertaining to renal function. The most commonly used sequences in MRI of the musculoskeletal system are only a small sample of the robust capability of this imaging modality. Advances in imaging of hardware and evaluation of cartilage as well as new application of previously proven techniques and clinically relevant progress in the realm of functional imaging will ensure MRI’s continued relevance to the orthopaedic surgeon.


