1. Basic Principles of Musculoskeletal MRI

BOOK CHAPTER

Basic Principles of Musculoskeletal MRI

Nancy M. Major MD (chapter://search/Major%20Nancy M./%7B%22type%22:%22author%22%7D), Mark W. Anderson MD (chapter://search/Anderson%20Mark W./%7B%22type%22:%22author%22%7D), Clyde A. Helms MD (chapter://search/Helms%20Clyde A./%7B%22type%22:%22author%22%7D), Phoebe A. Kaplan MD (chapter://search/Kaplan%20Phoebe A./%7B%22type%22:%22author%22%7D) and Robert Dussault MD (chapter://search/Dussault%20Robert/%7B%22type%22:%22author%22%7D)
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Although a detailed understanding of nuclear physics is not necessary to interpret magnetic resonance imaging (MRI) studies, it also is unacceptable to read passively whatever images you are given without concern for how the images are acquired or how they might be improved. Radiologists should have a solid understanding of the basic principles involved in acquiring excellent images. This chapter describes the various components that go into producing high-quality images, stressing the fundamental principles shared by all MRI scanners.

Every machine is different. Clinical scanners are now available at strengths ranging from 0.2 tesla (T) to 3.0T. Additionally, each vendor has its own language for describing its hardware, software, and scanning parameters, and an entire chapter could be devoted to deciphering the terms used by different manufacturers. Time spent learning the details of your machine with your technologists or physicists would be time well spent. If you are interested, read one of the excellent discussions of MRI physics in articles or other textbooks because, for the most part, in this book we leave the physics to the physicists.

What Makes a Good Image?

Lack of Motion

Motion is one of the greatest enemies of MRI (Fig. 1.1 (f0010)). It can arise from a variety of sources, such as cardiac motion, bowel peristalsis, and respiratory movement. For most musculoskeletal applications, motion usually stems from body movement related to patient discomfort. Patient comfort is of paramount importance because even if all the other imaging parameters are optimized, any movement would ruin the entire image.

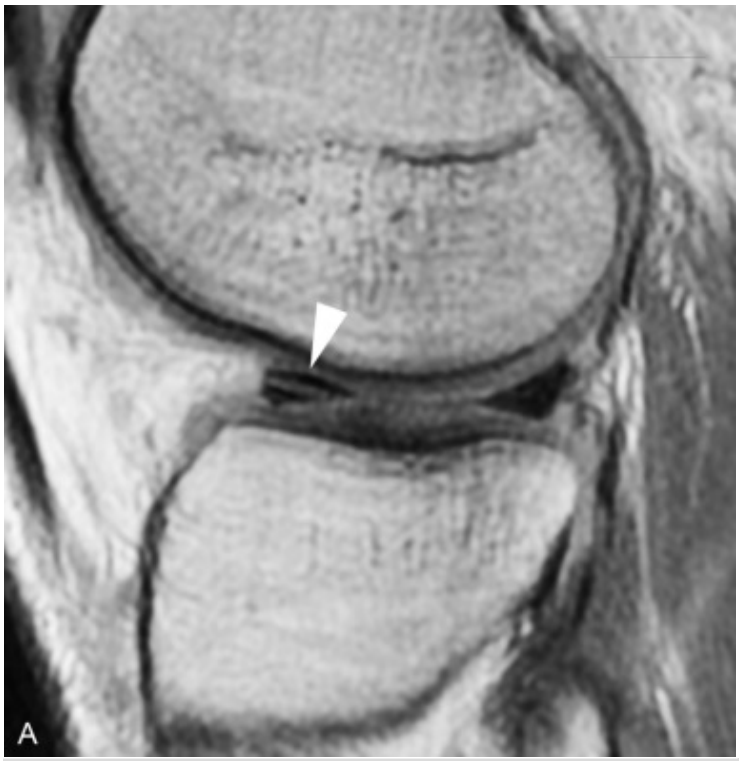
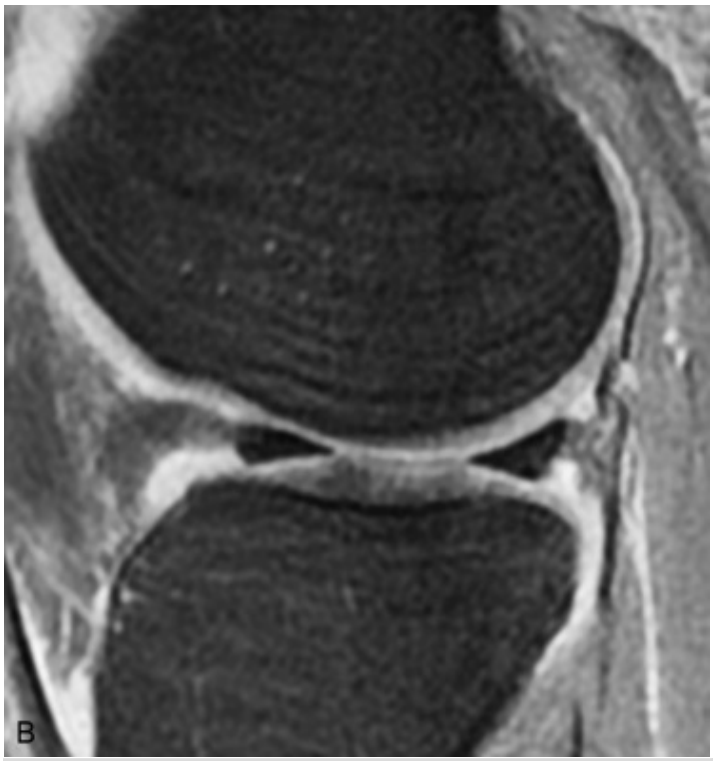


Fig. 1.1

Effect of motion. **A** , Sagittal proton density–weighted image of the knee. There is marked motion artifact and linear increased signal suggestive of a tear in the anterior horn of the lateral meniscus (*arrowhead*). **B** , Sagittal proton density with fat saturation is also degraded by motion artifacts but confirms that the meniscus is intact and that the meniscal signal abnormality was secondary to motion artifact.



Patient comfort begins with positioning. Every effort should be made to make the patient comfortable, such as placing a pillow beneath the knees when the patient is supine to reduce the stress on the back or providing padding at pressure points. When the patient is in a comfortable position, passive restraints, such as tape, foam rubber, or sandbags, can be used for maximal immobilization. Music via headphones can help alleviate anxiety. Short-acting sedation may be required for claustrophobic patients.

Another cause of patient motion is a prolonged examination, which is one reason why streamlined imaging protocols are useful. By designing efficient imaging sequences, the necessary scans are obtained in as short a time as possible, resulting in better patient compliance, improved technologist efficiency, and maximal scanner throughput. Standardized protocols also reduce the need for direct physician oversight during the scan and allow for improved image interpretation because the radiologist views the same anatomy in the same imaging planes utilizing the same sequences each time.

Signal and Resolution (Table 1.1) (t0010)

Signal is the amount of information on an image. Other factors are important, but if the image is signal-poor (i.e., “noisy”), even the best radiologist would be unable to interpret it (Fig. 1.2 (f0015)).

Table 1.1

Signal and Resolution: Life's Tradeoffs

↑ Signal/↓ Resolution	↑ Resolution/↓ Signal
↑ Slice thickness	↓ Slice thickness

↑ Signal/↓ Resolution	↑ Resolution/↓ Signal
↑ Field of view	↓ Field of view
↓ Imaging matrix	↑ Imaging matrix

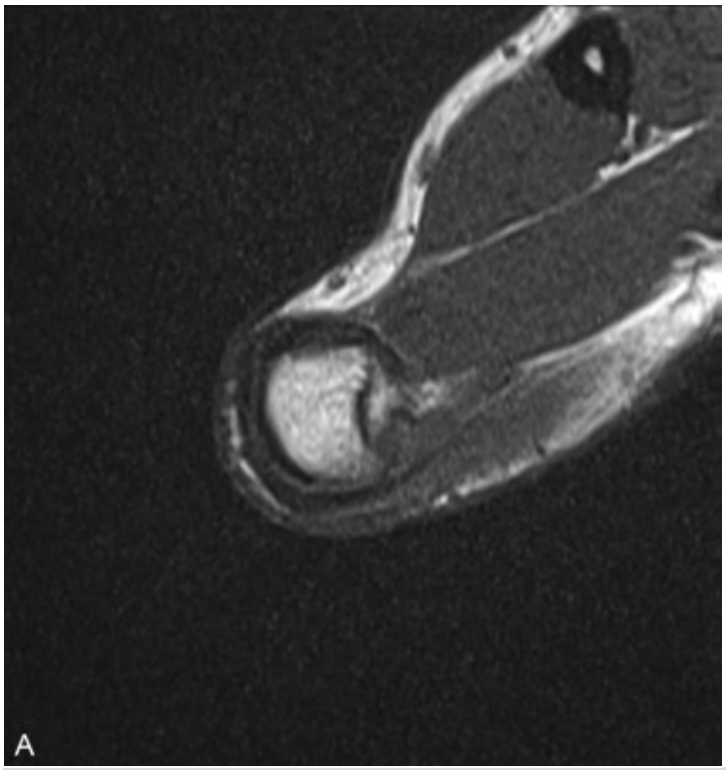
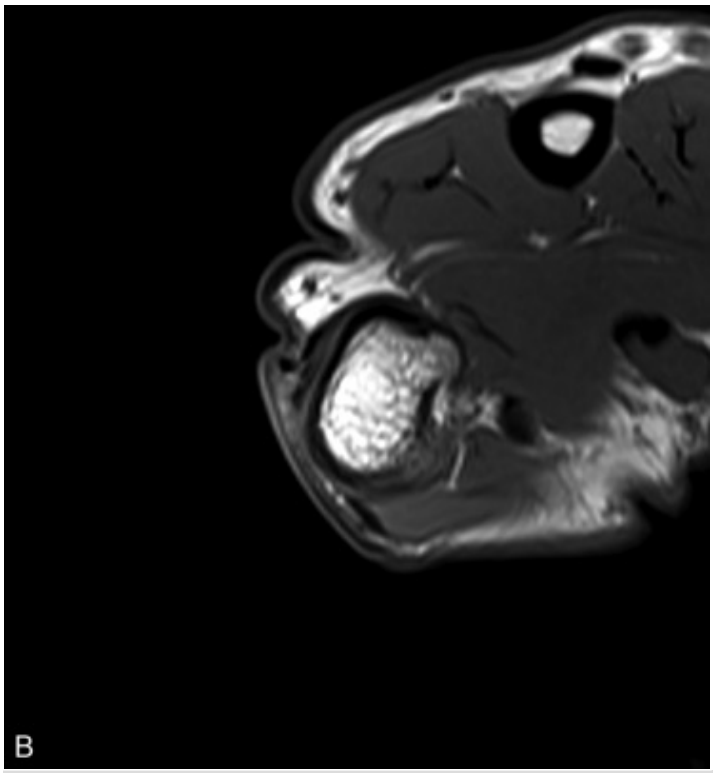


Fig. 1.2

Image noise and effect of surface coil. A , Axial T1-weighted image of the thumb obtained with a phased array extremity coil is of very poor quality, primarily related to prominent image noise. **B** , A follow-up axial T1-weighted image at the same level obtained with a dedicated wrist coil demonstrates markedly improved image quality due to an improved signal-to-noise ratio.



Each image is composed of *voxels* (volume elements) that correspond to small portions of tissue within the patient. One dimension of the voxel is defined by the *slice thickness* . The other dimensions are determined by the *field of view* and *imaging matrix* (number of squares in the imaging grid) (Fig. 1.3 (f0020)). Because the signal is proportional to the number of protons resonating within each voxel, anything that increases the size of the voxel would increase the signal (Fig. 1.4 (f0025)). Increasing slice thickness or field of view or, alternatively, decreasing the matrix (spreading the imaging volume over fewer but larger boxes) would increase the signal.

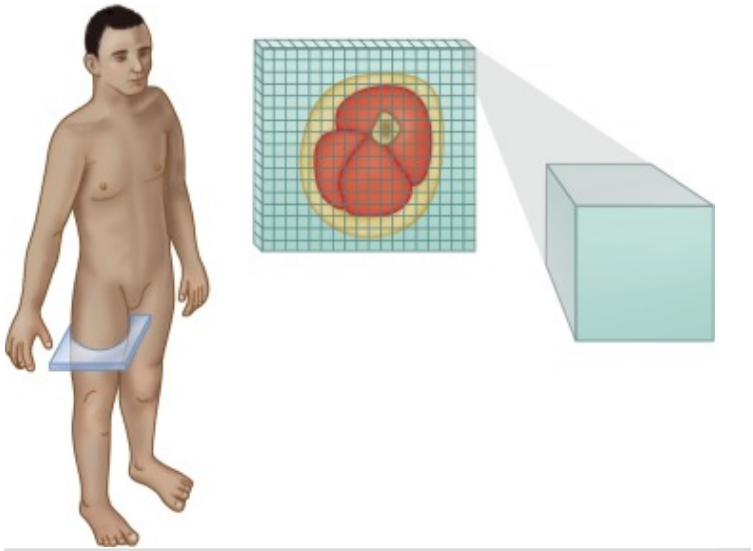


Fig. 1.3

Imaging voxel . Schematic diagram illustrating the imaging matrix and an individual voxel from an axial MR image of the proximal thigh.

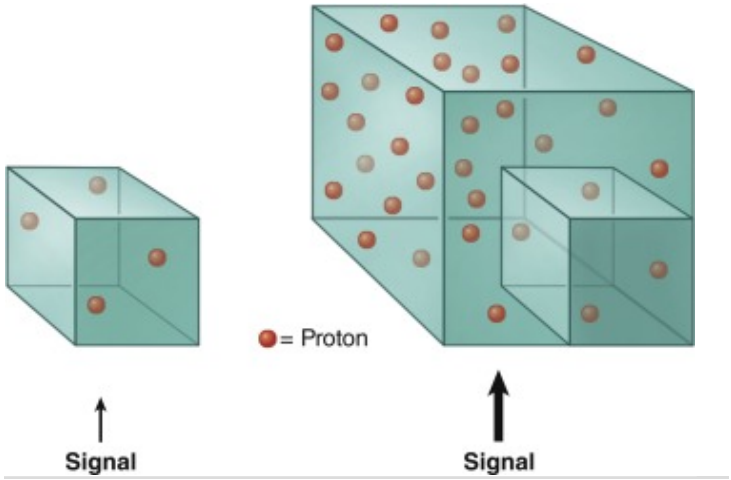


Fig. 1.4

Voxel size versus signal. Signal is directly proportional to the number of protons within the voxel. Note the larger number of protons and the resulting increased signal in the larger imaging voxel.

Another factor that affects the signal is the number of *signal acquisitions* (also known as the number of *signal averages* or *number of excitations [NEX]*). A signal average of 2 means that the signal arising from the protons in each voxel is collected twice, resulting

in a doubling of the imaging time. This results in an increase in the signal-to-noise ratio of the square root of 2. As a result, this is a relatively time-inefficient method for improving signal.

Finally, signal may be adversely affected if the slices are obtained too close together because of the phenomenon of “cross talk.” When adjacent slices are acquired, some interference from one slice may spill over into the adjacent slice, resulting in increased noise. This is especially true for T2-weighted sequences. This effect is lessened by interposing a “gap” between the slices (a small portion of tissue that is not imaged), resulting in decreased noise and increased signal. Typical gaps range from 10% to 25% of the slice thickness. The larger the gap, the greater the amount of unimaged tissue, and the greater the possibility of missing a small lesion.

Sequences can be employed that can eliminate the artifacts due to motion, pulsatile flow, and cross talk unique to each magnet manufacturer. These sequences are particularly useful if the patient demonstrates anxiety or has an involuntary spasm that can preclude obtaining desirable images.

Now that we have discussed several ways to improve the signal of the image (also known as *increasing the signal-to-noise ratio*), we need to look at the second major factor that makes for a good image: *resolution* . Resolution is the ability to distinguish small objects. It is absolutely critical in most musculoskeletal applications, given the relatively small structures that are often the subject of inquiry.

As in life, there is no such thing as a free lunch in MRI, and any changes designed to improve resolution negatively affect the signal. Decreasing the size of the voxel (by decreasing slice thickness, decreasing the field of view, or increasing the imaging matrix) not only would improve resolution but also would decrease the number of protons in each voxel and decrease the signal (see Table 1.1 (t0010)). Consequently, when designing imaging protocols, there is always a compromise between (1) maximizing signal and (2) optimizing resolution (Fig. 1.5 (f0030)). Another factor, coil selection, can help minimize this tradeoff.

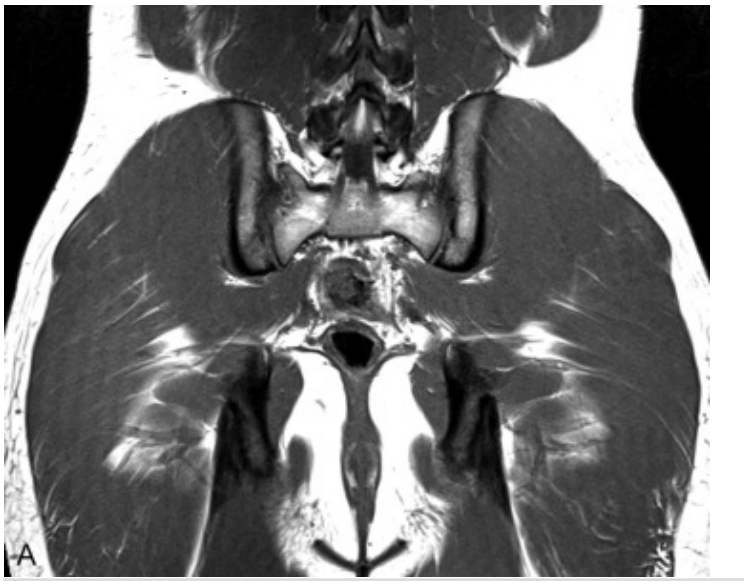
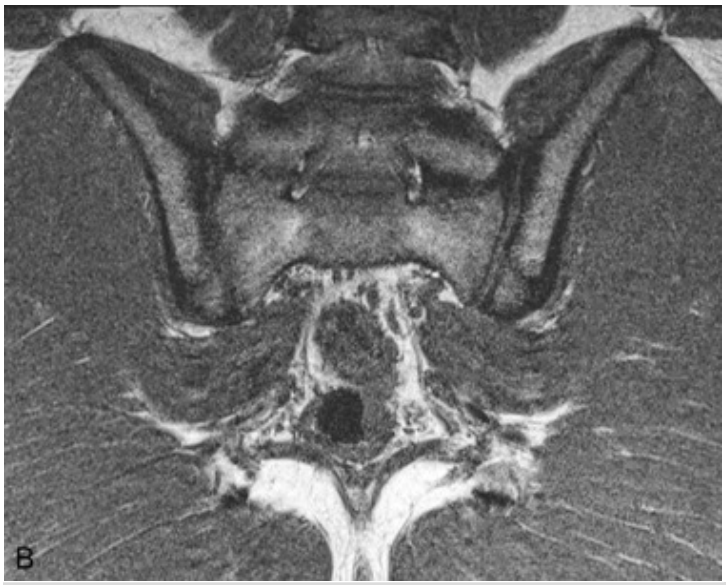


Fig. 1.5

Image noise versus resolution: effect of field of view. A , Coronal T1-weighted, large-field-of-view image of the pelvis. Note the good signal-to-noise ratio. **B** , An oblique T1-weighted image using the same coil but smaller field of view. The resolution in this image is actually higher than in the prior image, but the overall image quality is poor due to the increased image noise.



An MR image is created using the signal that returns from resonating protons within tissue. Just as it is easier to hear a speaker's voice the closer he or she is to you, the closer the receiver coil is to the tissues of interest, the better the signal and the lower the noise.

In MRI, every attempt should be made to use the smallest coil possible to produce the maximum signal. Coils that can be placed on or close to the body part of interest are called *surface coils* and result in markedly improved signal compared with the *body coil* . A factor that must be considered when selecting a coil relates to its size. A coil must be able to detect signal from the entire length and depth of the tissues of interest; for a flat surface coil, the depth of penetration equals roughly half of the coil's diameter or width. Beyond this distance, the signal begins to drop off, as evidenced by decreasing signal in that region of the image. To avoid this problem, so-called *volume coils* are often used in the extremities. These encircle the arm or leg, providing uniform signal throughout the tissues of interest. Most coils also are now constructed with a phased array design. A phased array coil is composed of several

smaller coils placed in a series, resulting in maximal signal from each small coil and from each segment of tissue covered by the coils. The use of a surface coil usually provides more than adequate signal and allows for the use of high-resolution imaging parameters. Selecting the appropriate coil is paramount to obtaining signal rich and high-resolution images.

Tissue Contrast

Both computed tomography (CT) and MRI are capable of producing high-resolution scans, but the superior soft tissue contrast of MRI (the ability to differentiate types of tissue based on their signal intensities) sets it apart. A CT image is based on the x-ray attenuation properties of tissues, whereas soft tissue contrast in MRI is related to differences in proton resonance within the tissues. The protons within fat resonate differently than the protons in fluid, and by changing the imaging parameters at the MRI console, differences in these tissue-specific properties can be emphasized. This is known as *weighting* the image. Tissues can be differentiated based on their signal intensities on various sequences. The signal intensity of a tissue on MRI should be described in relative terms (e.g., hyperintense relative to muscle) because the gray scale values of the image are not assigned in a quantitative fashion, as with CT, but are scaled relative to the brightest voxel on the image.

Pulse Sequences (Tables 1.2 and 1.3) (t0015)

The collection of specific imaging parameters selected for a single scan is called a *pulse sequence* . A typical musculoskeletal examination includes three to six sequences obtained in various anatomic planes. There are many different kinds of sequences, and

each has specific strengths and weaknesses. We do not want to get bogged down in technical details at this point; in the following discussion, typical imaging parameters for each pulse sequence are provided in parentheses. These are summarized in Table 1.3 (t0020) , and there is a glossary at the end of the chapter to help with understanding any unfamiliar terms.

Table 1.2

Pulse Sequences: Strengths and Weaknesses

Sequence	Strength	Weakness
Fast Spin Echo		
T1	Anatomic detail Fat, subacute hemorrhage Gd-DTPA enhancement (with fat saturation) Marrow pathology	Poor detection of soft tissue edema and other T2-sensitive pathology Not as sensitive as STIR or FSE-T2 with fat saturation for marrow pathology
Proton density	Anatomic detail Meniscal pathology	Poor detection of fluid and marrow pathology when not combined with fat saturation
T2	Detection of fluid and many pathologic processes Excellent detection of marrow pathology when combined with fat saturation Good in patients with metal hardware (↓ susceptibility effects)	Poor detection of marrow pathology when not combined with fat saturation
Gradient Echo		

Sequence	Strength	Weakness
T2*	Fibrocartilage (meniscus, labrum) Loose bodies and hemorrhage (↑ susceptibility effects) 3D imaging	Poor detection of marrow pathology at high field strengths Metallic hardware (↑↑artifacts due to susceptibility effects)
STIR	Marrow and soft tissue pathology	Should not be used with Gd-DTPA

Gd-DTPA, Gadolinium-DTPA; STIR, short tau inversion recovery.

Table 1.3

Pulse Sequences: Imaging Parameters (or "How to Recognize a Sequence by the Numbers")

Sequence	TR (msec)	TE (msec)	TI (msec)	Flip Angle (°)	ETL
T1	≤ 800	≤ 30	N/A	90	N/A
Proton density	≥ 1000	≤ 30	N/A	90	N/A
FSE T2	≥ 2000	≥ 50	N/A	90	2-16
FSE STIR	≥ 2000	≥ 30	120-180	180 → 90	2-16
GRE T1	Variable	≤ 30	N/A	70-110	N/A
GRE T2*	Variable	≤ 30	N/A	5-20	N/A

ETL , Echo train length; *FSE* , fast spin echo; *GRE* , gradient echo; *TE* , echo time; *TI* , inversion time; *TR* , repetition time.

Spin Echo

Conventional spin echo pulse sequences include T1-weighted (T1W), T2-weighted (T2W), and proton density (PD)–weighted sequences (see Table 1.3 (t0020)).

T1

T1 (repetition times [TR] < 800 msec; echo times [TE] < 30 msec) is considered a "short TR, short TE" sequence. Fat and subacute hemorrhage are bright on these images (Fig. 1.6 (f0035)). Proteinaceous fluid (as in an abscess or ganglion cyst) may be of intermediate or high signal intensity, depending on the protein content. Most other soft tissues are of intermediate to low signal intensity on T1W images, and fluid is especially low (hypointense relative to muscle or intervertebral disk) (Fig. 1.7 (f0040) and Table 1.4 (t0025)). T1W images are useful for delineating anatomic planes, marrow architecture, fat content within masses, and subacute hemorrhage. T1W sequences are also used to evaluate tissue enhancement after intravenous (IV) administration of gadolinium–DTPA (Gd-DTPA) (see later in this chapter).

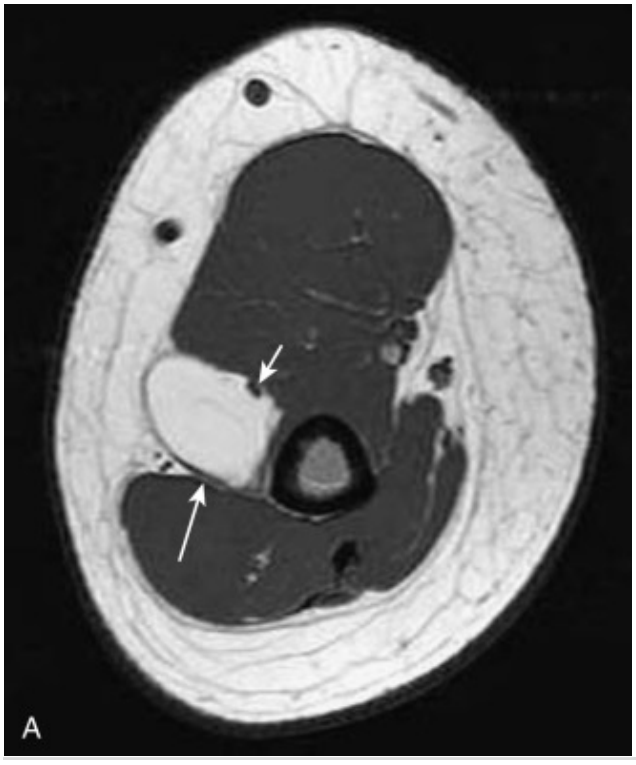
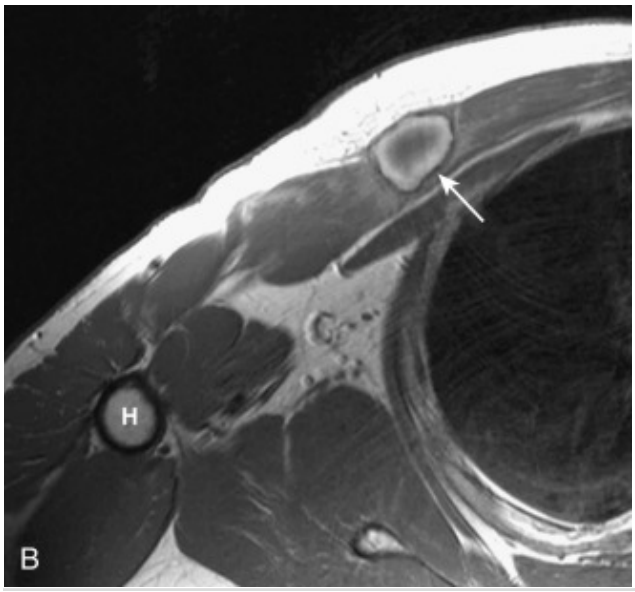


Fig. 1.6

T1-weighted images: high signal intensity tissues. A , T1 axial image of the upper arm. Note the high-signal-intensity subcutaneous fat and intermuscular lipoma (*large arrow*) between the biceps and triceps muscles. The mass partially surrounds the radial nerve (*small arrow*). **B,** T1 axial image of the right axilla. There is a well-circumscribed mass within the right pectoralis major muscle in this 55-year-old man, who felt a “pop” while playing Frisbee golf. Note the high-signal-intensity rim along the periphery of this subacute hematoma (*arrow*). *H,* Humerus.



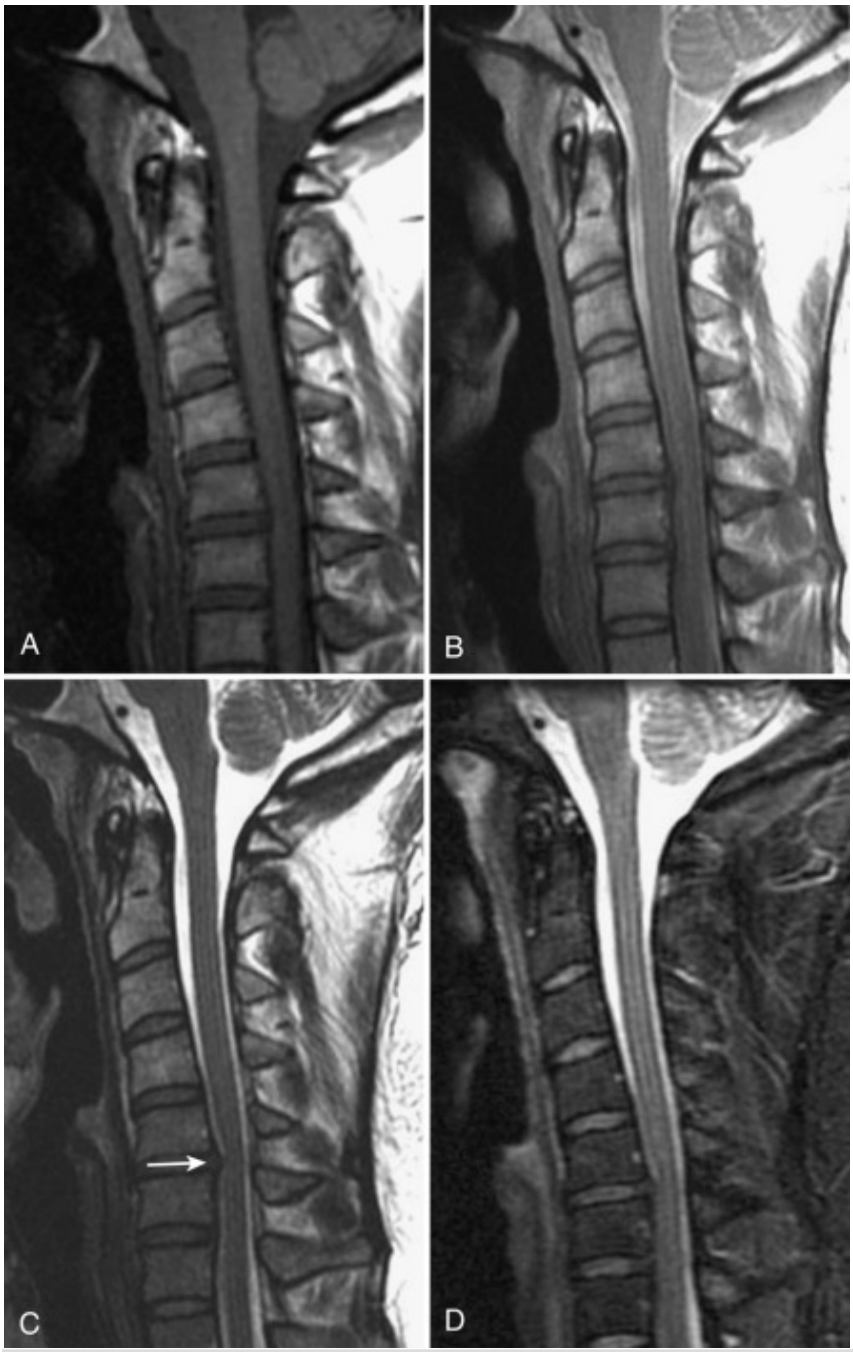

A
B
C
D

Fig. 1.7

Fluid signal intensity. A , T1 sagittal image of the cervical spine. The cerebrospinal fluid shows lower signal intensity relative to the intervertebral disks. **B,** Proton density sagittal image of the cervical spine. The fluid is slightly hyperintense to disk. **C** , FSE-T2 sagittal image of the cervical spine. The signal intensity of the fluid is strikingly hyperintense to disk. Note also the disk protrusion deforming the cord at the C5–C6 level (*arrow*). **D** , Sagittal STIR image of the cervical spine. The cerebrospinal fluid remains hyperintense relative to disk, but note the diffuse suppression of signal from fat.

Table 1.4

Tissue Signal Intensity: T1 and T2

	T1	T2
Fat	↑↑	↑
Subacute hemorrhage	↑↑	↑↑
Proteinaceous fluid	↑	↑↑
Fluid	↓	↑↑
Fibrous tissue/scar	↓	↓ or ↑
Cortical bone	↓↓	↓↓
Chronic hemorrhage/hemosiderin	↓↓	↓↓
Air	↓↓	↓↓

↑, Brighter than muscle; ↓, darker than muscle.

T2

T2 (TR > 2000 msec; TE > 60 msec) is considered a “long TR, long TE” sequence. Fluid is bright on T2W images (see Fig. 1.7 (f0040)). Likewise, most pathologic processes (e.g., tumor, infection, injury) are often highlighted on T2W images because of their increased fluid content. Fat is less bright than on T1W images, and muscles remain of intermediate signal intensity. Conventional spin echo sequences have been a part of most imaging protocols in the past but now are rarely, if ever, used because of their relatively long imaging times. As such, they have been replaced by fast spin echo (FSE) sequences.

Proton Density

PD (TR > 1000 msec; TE < 30 msec) is considered an “intermediate TR, short TE” sequence. Also known as *spin density,* these images represent a mixture of T1 and T2 weighting, with contrast being primarily a function of the number of protons within each tissue. This sequence also provides good anatomic detail but relatively little overall tissue contrast because of its intermediate weighting (see Fig. 1.7 (f0040)).

Fast Spin Echo

FSE, also known as *turbo spin echo,* allows for much more rapid acquisition of images than the conventional spin echo method. Several samples are acquired in the time one sample is obtained with a conventional spin echo technique (Fig. 1.8 (f0045)). The time saved is directly proportional to the number of samples (also designated as the *echo train length*). An FSE sequence with an echo train length of 4 would acquire the same amount of information as a conventional spin echo sequence in one fourth the time.

Decreased overall imaging time lessens the potential for patient motion. Alternatively, the time saved can be used for obtaining additional signal averages to improve signal. FSE sequences are commonly used in musculoskeletal imaging.

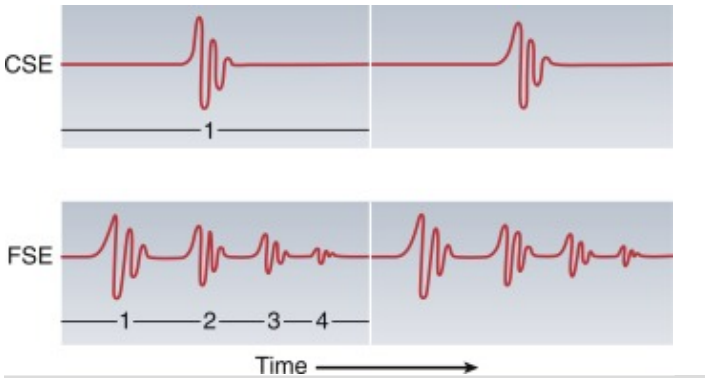


Fig. 1.8

Conventional versus FSE pulse sequences. Diagram showing the efficiency of an FSE sequence in which four echoes are obtained within a single repetition time compared with one echo using a conventional spin echo (CSE) technique.

This technique has some drawbacks. First, the signal intensity of fat remains quite bright on FSE–PD and T2W images. Consequently, pathology in subcutaneous fat or marrow may be obscured on these images because of the similar signal intensity of fat and fluid. This problem can be overcome by combining this technique with fat saturation (see later in this chapter) (Fig. 1.9 (f0050)).

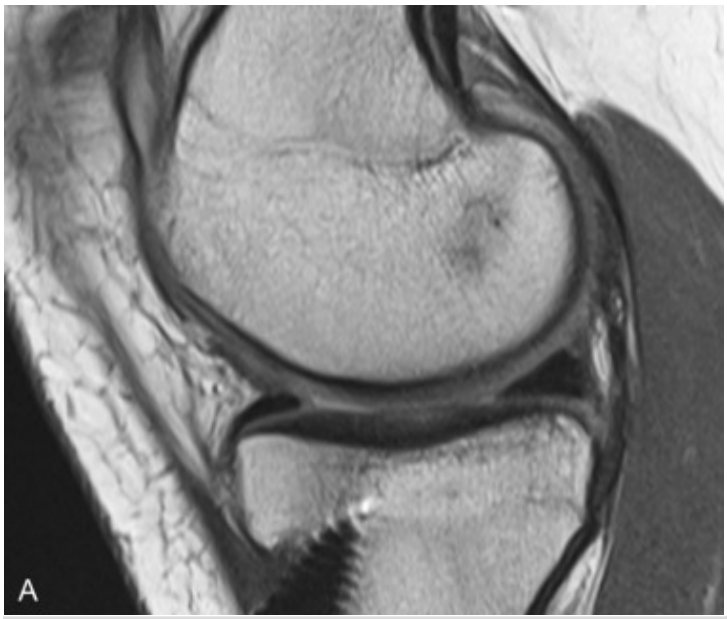
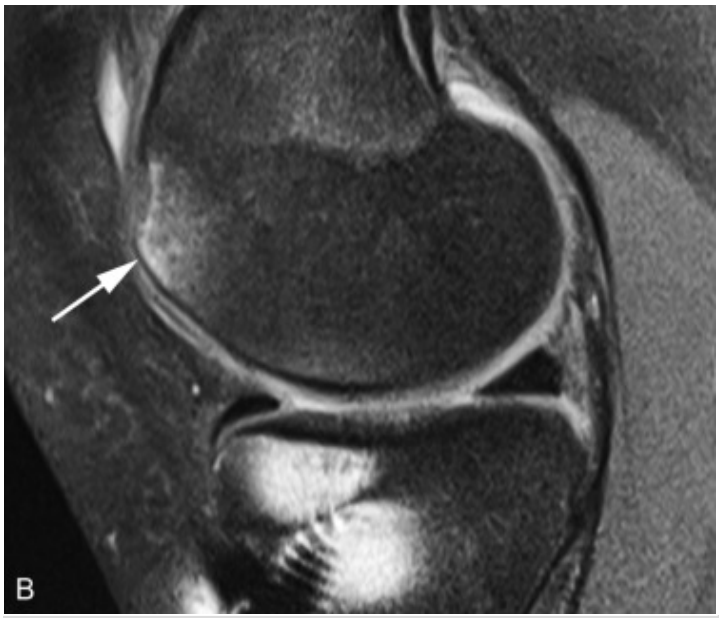


Fig. 1.9

Effect of fat saturation. A , Sagittal fast spin echo (FSE) proton density image of the knee. There is some artifact around a tibial screw related to a prior anterior cruciate ligament (ACL) reconstruction but no evidence of marrow contusion. **B,** Sagittal FSE proton density–weighted image with fat saturation reveals a focal, high-signal-intensity contusion in the anterior aspect of the medial femoral condyle (*arrow*). Note also the incomplete fat saturation adjacent to the tibial screw.



Second, the FSE technique can result in blurring along tissue margins, especially when PD-weighted images are acquired using long echo train lengths (> 4). Although it is tempting to use a longer echo train length to decrease imaging time, the associated increase in blurring may result in missing some types of pathology, such as meniscal tears in the knee (Fig. 1.10 (f0055)).

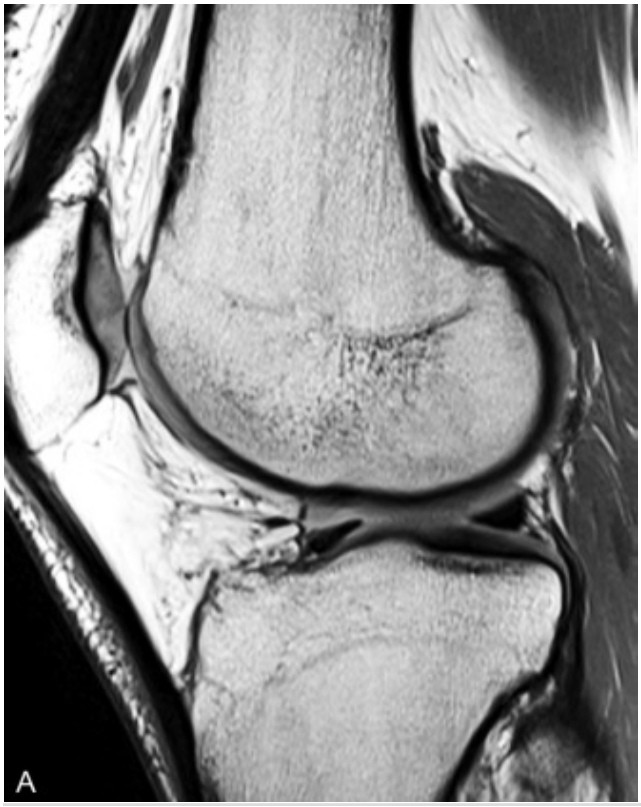
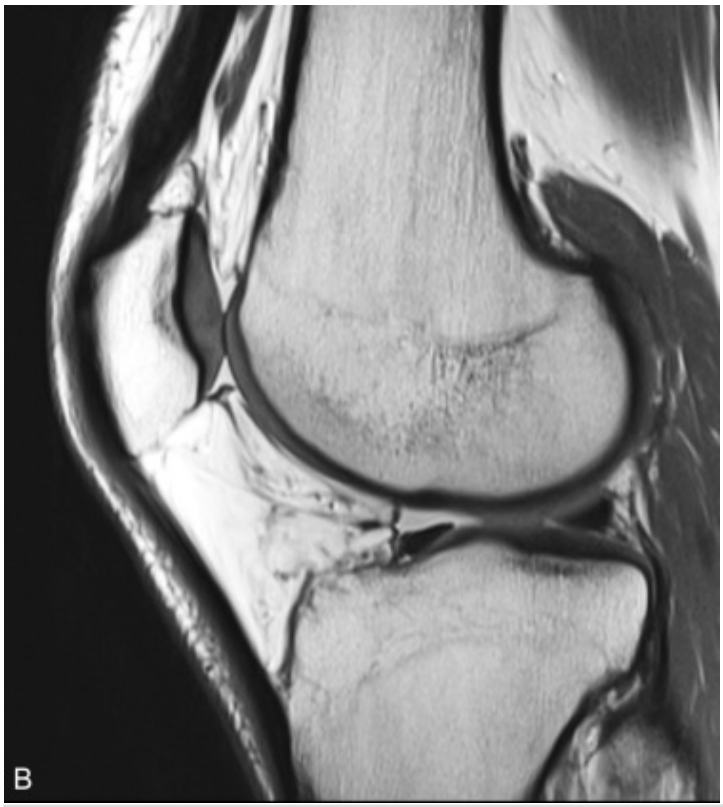


Fig. 1.10

Blurring artifact: FSE proton density. Sagittal FSE proton density–weighted images of the knee obtained with echo train lengths (ETLs) of **A,** 5 and **B,** 21. Note the increased amount of blurring in the image obtained with the longer ETL.



Inversion Recovery

Historically known as *short tau inversion recovery* (STIR) imaging, inversion recovery (TR > 2000 msec; TE > 30 msec; TI = 120-180 msec) is a fat-saturation technique that results in markedly decreased signal intensity from fat and strikingly increased signal from fluid and edema (Fig. 1.11 (f0060)). As a result, inversion recovery is an extremely sensitive tool for detecting most types of soft tissue and marrow pathology. We use an FSE-STIR sequence with most of our musculoskeletal protocols. The FSE-STIR sequence does not suffer from the long imaging times, limited number of slices, and poor signal that plagued older, conventional STIR sequences. For the remainder of this book, when the term *STIR* is used, it refers to the FSE-STIR technique, unless otherwise indicated. On a practical note, FSE-STIR imaging is, in many respects, equivalent to an FSE-T2W sequence with frequency-selective fat saturation (see later in this chapter), and many

clinicians use these sequences interchangeably. STIR imaging typically provides more consistently homogeneous fat suppression than the frequency-selective technique (see later in chapter).

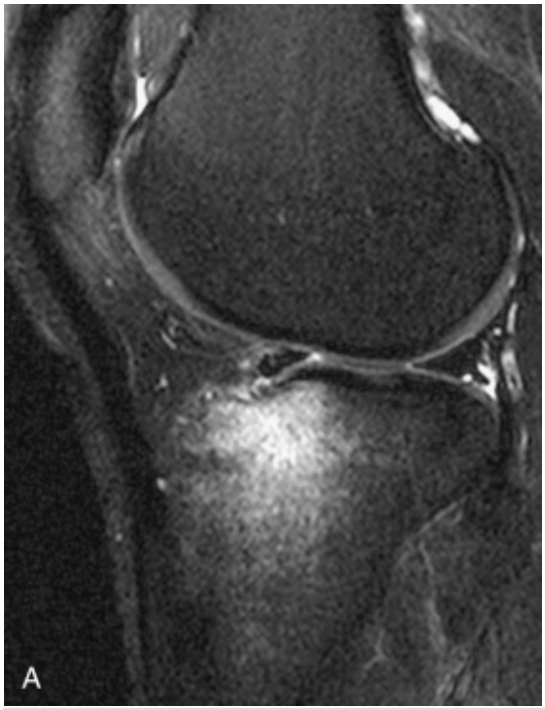
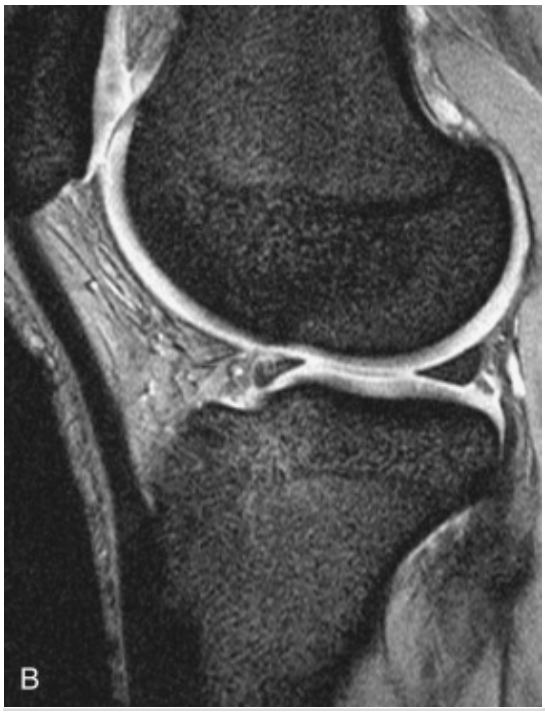


Fig. 1.11

Fat-saturated T2 versus gradient echo sequences for marrow pathology. **A** , FSE-T2 sagittal image of the knee with fat saturation. There is a focal marrow contusion involving the anterior portion of the tibial plateau. Note the conspicuity of the contusion relative to the dark, suppressed marrow fat. **B,** Gradient echo T2* sagittal image of the knee. The contusion is much less apparent because of susceptibility effects of the trabecular bone in the tibial plateau.



Gradient Echo

The gradient echo (TR variable; TE < 30 msec; flip angle = 10-80 degrees) family of pulse sequences was originally developed to produce T2W images in less time than was possible with a conventional spin echo technique. As their names imply, gradient echo and spin echo pulse sequences acquire images in different ways. Consequently, although fluid appears bright on gradient echo T2W images (designated T2*W) and (fast) spin echo–T2W images, the appearance of other tissues differs on the two sequences. Ligaments and articular cartilage are particularly well shown with gradient echo sequences, as are fibrocartilaginous structures such as the knee menisci and glenoid labrum. Contrast between other soft tissues is relatively poor, however, on gradient echo images.

Gradient echo imaging can be performed using a two-dimensional technique (in which slices are obtained individually) or a three-dimensional (3D) “volume” technique. In 3D imaging, the signal from an entire volume of tissue is obtained at one time, and these

data can be partitioned into extremely thin (< 1 mm) slices such that the voxel dimensions are nearly isotropic (equal in all dimensions) (Fig. 1.12 (f0065)). This technique allows for high-resolution imaging and is especially useful when evaluating extremely small structures, such as ligaments in the wrist. These 3D sequences also provide the ability to create reformatted images in virtually any plane without a significant loss of resolution (Fig. 1.13 (f0070)). Although most 3D sequences require relatively long imaging times (introducing the potential for motion artifact), if the reformatted images are of adequate quality, other sequences may be omitted from the protocol, minimizing this effect.

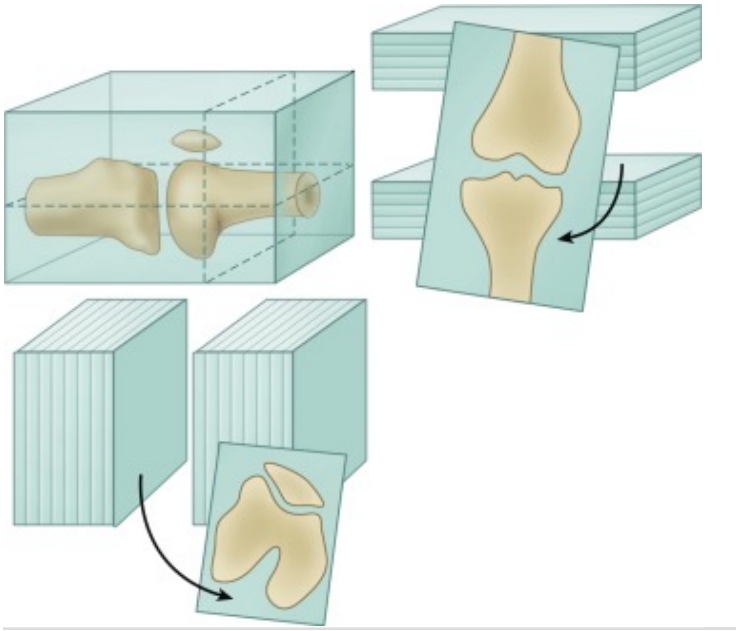


Fig. 1.12

3D imaging. Diagram showing axial and coronal reconstructions from a single-acquisition 3D volume sequence.

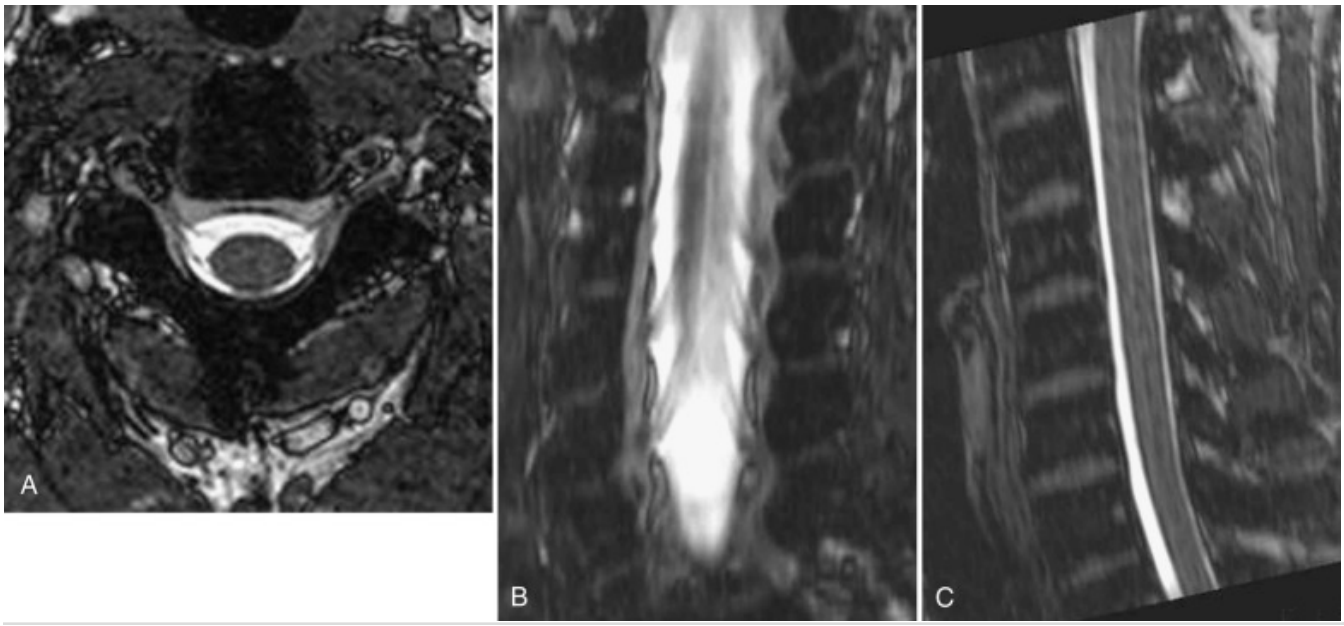


Fig. 1.13

3D volume imaging. A , T2* gradient echo axial image of the cervical spine (obtained with a 3D technique). There is excellent contrast between the high-signal-intensity cerebrospinal fluid and low-signal-intensity spinal cord and exiting nerve roots. **B,** Coronal reformatted image of the cervical spine (from the axial dataset). The cord and nerve roots are well shown within the bright cerebrospinal fluid. **C** , Sagittal reformatted image of the cervical spine (from the axial dataset). The myelographic effect of the bright cerebrospinal fluid reveals no disk bulge or protrusion.

One feature of gradient echo sequences is a heightened sensitivity to *susceptibility effects* . This refers to artifactual signal loss at the interface between tissues of widely different magnetic properties, such as metal and soft tissue. This feature can be advantageous when searching for subtle areas of hemorrhage because these would be more conspicuous on gradient echo images due to susceptibility effects of the hemoglobin breakdown products within the tissue (Fig. 1.14 (f0075)). Similarly, these sequences are useful for detecting loose bodies and soft tissue gas because of susceptibility effects.

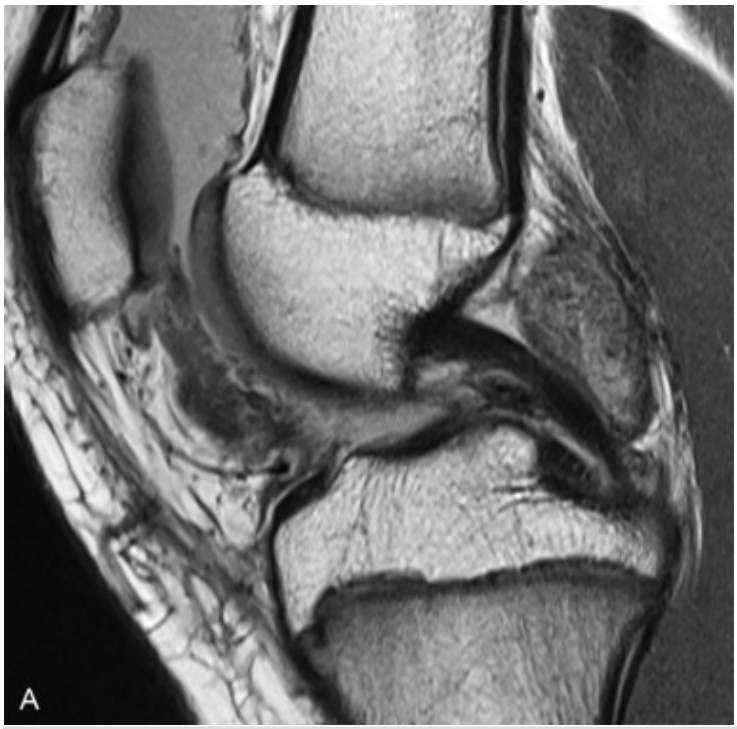
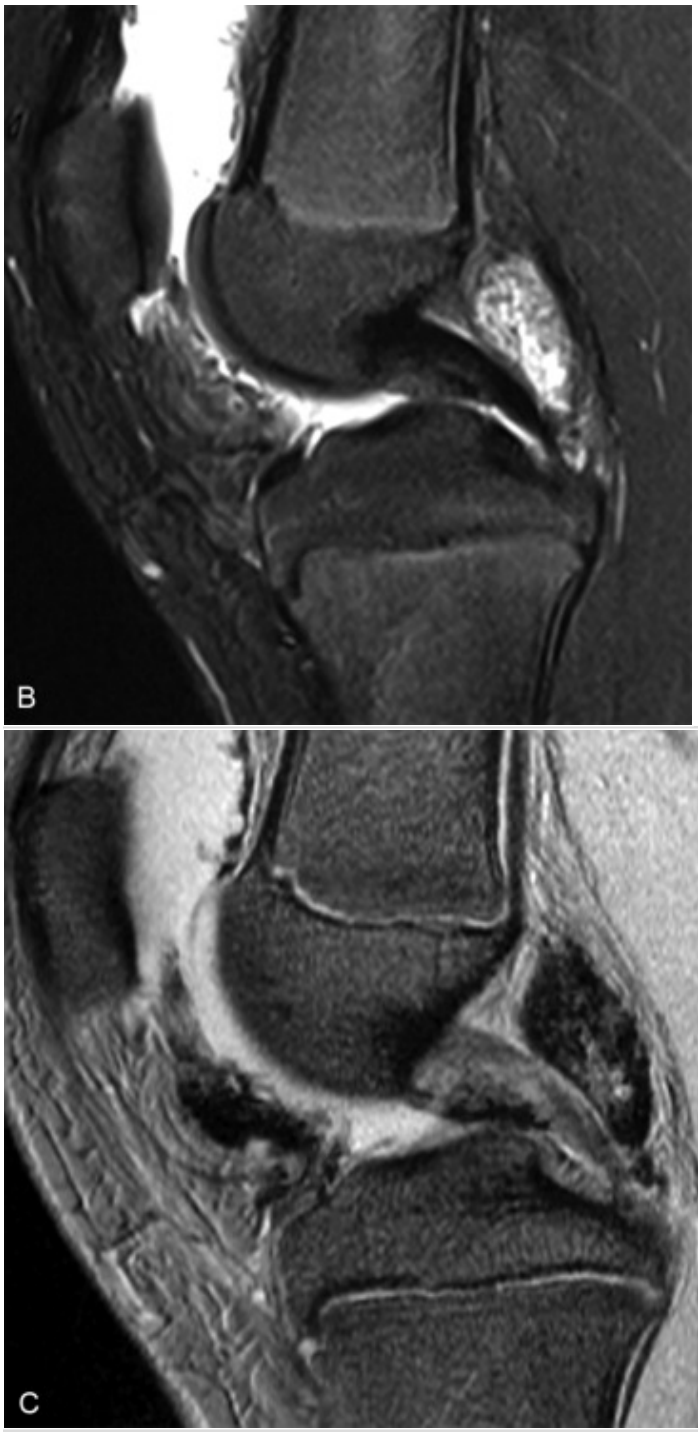


Fig. 1.14

Gradient echo imaging: susceptibility effect. A , Sagittal FSE proton density–weighted image of the knee. Low-signal-intensity tissue is present in the posterior joint and Hoffa's fat pad. **B,** Sagittal STIR image. Portions of the tissue remain of intermediate to low signal intensity. **C** , Sagittal gradient echo T2* weighted image. Note the markedly decreased signal intensity and increased conspicuity ("blooming") of the tissue due to susceptibility effects of the hemosiderin—in this case of pigmented villonodular synovitis (PVNS).



Conversely, drawbacks of these susceptibility effects include overestimating the size of osteophytes in spine imaging and missing marrow pathology when trabecular bone is not destroyed, because a susceptibility artifact at the interfaces between trabecular bone and marrow fat obscures the associated edema (see Fig. 1.11 (f0060)). Susceptibility effects can also be problematic when imaging patients with metallic hardware because of obscuration of adjacent normal tissue by the susceptibility artifacts. FSE sequences tend to

minimize susceptibility artifacts and are useful when imaging patients with a history of prior surgery, especially if it is known that metallic hardware is present (Fig. 1.15 (f0080)).

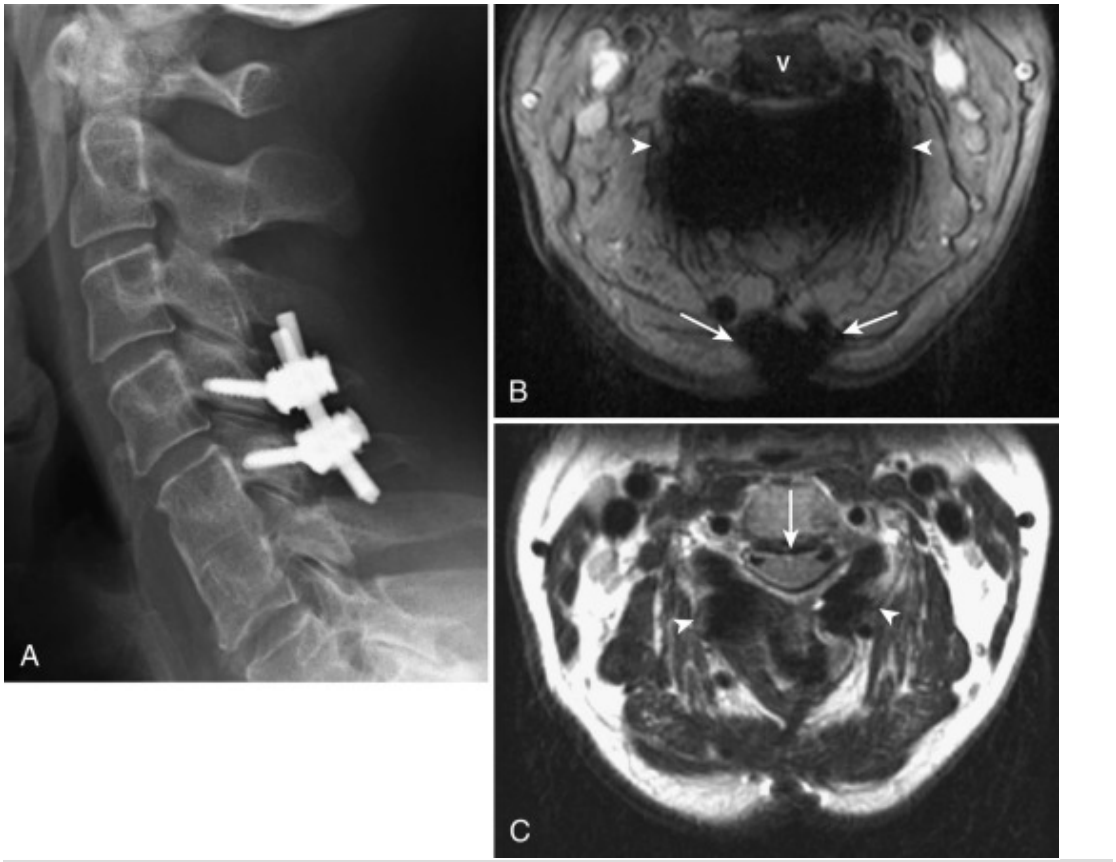


Fig. 1.15

FSE imaging: decreased susceptibility artifacts. A , Lateral radiograph of the cervical spine. Posterior hardware is present from a prior cervical fusion. **B,** Prominent susceptibility artifact from the hardware obscures adjacent structures, including the spinal canal and cord (*arrowheads*). Additional artifact related to other postoperative changes is evident in the more superficial tissues (*arrows*). *V* , Vertebral body. **C** , FSE-T2 axial image of the cervical spine (same level as in **B**). Note the decreased artifact related to the metal hardware (*arrowheads*) and the improved depiction of the spinal canal and contents (*arrow*).

Fat Saturation

There are certain clinical situations in which it is advantageous to suppress the high signal intensity of fat. Two main techniques are used to accomplish this: frequency-selective (chemical) fat saturation and STIR imaging.

Frequency-Selective

The frequency-selective technique exploits the differences in *resonant frequencies* between fat and water by applying a “spoiler” pulse at the frequency of fat. This pulse wipes out the signal from fat without affecting the signal from water. Likewise, the signal from Gd-DTPA (either IV or intra-articular) is preserved.

This technique can be used with T1W imaging to confirm the fatty nature of a mass (Fig. 1.16 (f0085)) and to distinguish between fat and hemorrhage, since both would be bright on non–fat-saturated T1W images, but fat would suppress, whereas hemorrhage would not. After the IV administration of Gd-DTPA contrast material, fat-saturated images make tissue enhancement more conspicuous (Fig. 1.17 (f0090)). Fat-saturated T1W images are also used with Gd-DTPA arthrography, allowing for the Gd-DTPA to be more conspicuously identified and improving diagnostic accuracy.

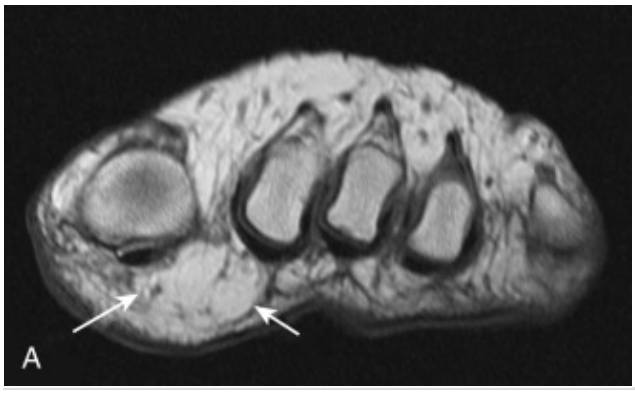
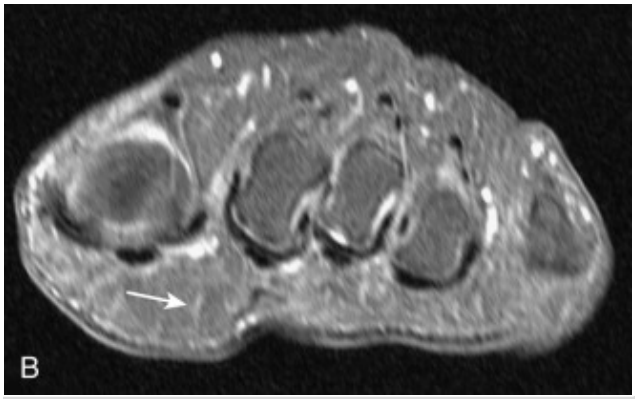


Fig. 1.16

Frequency-selective fat saturation. A , T1 short-axis image of the forefoot. There is an irregular lipoma within the plantar fat at the level of the first and second metatarsophalangeal joints (*arrows*). **B,** T1 short-axis image with fat saturation of the forefoot after IV injection of Gd-DTPA. There is complete suppression of the signal arising from this mass, with the exception of a thin intralesional septum (*arrow*) confirming its lipomatous nature.



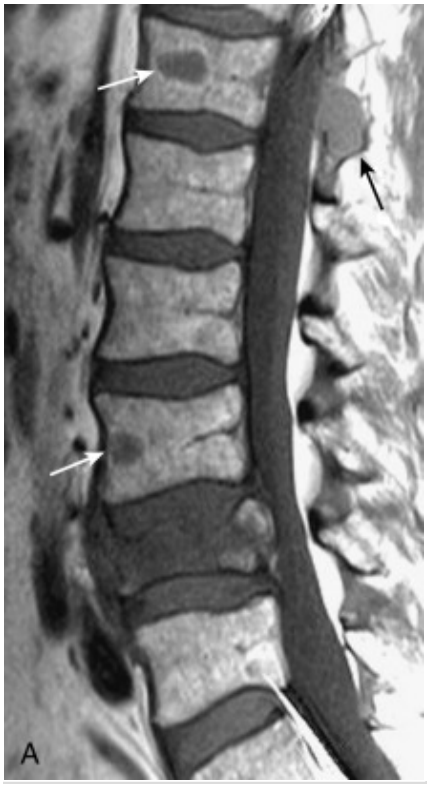
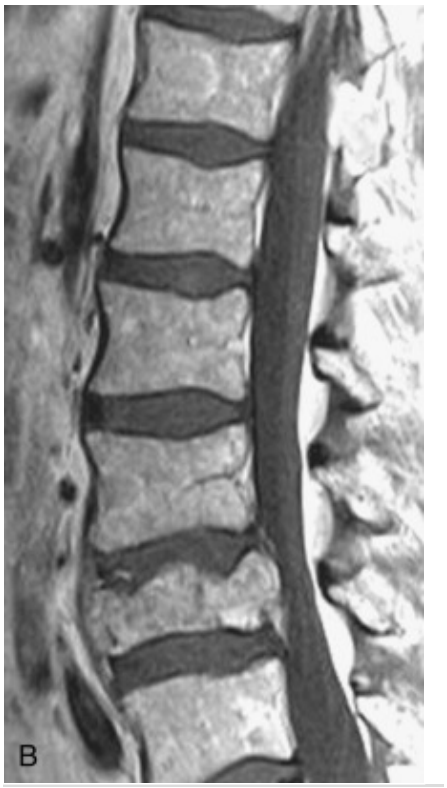
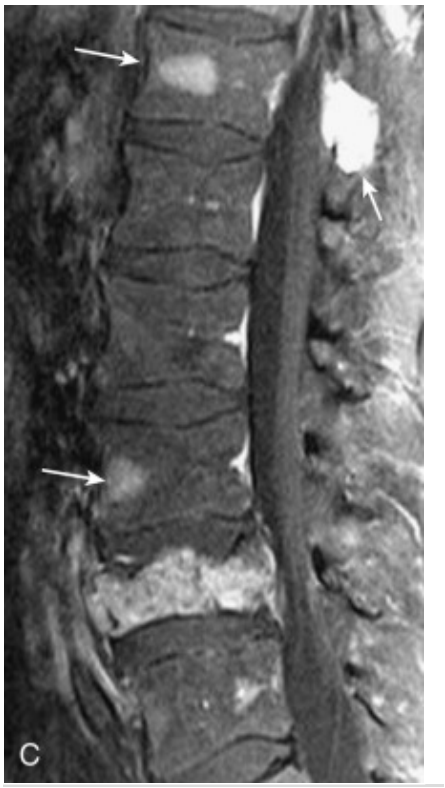


Fig. 1.17

Frequency-selective fat saturation and Gd-DTPA enhancement. A , T1 sagittal image of the lumbar spine. A pathologic burst fracture of the L4 vertebra is evident in this patient with myeloma. Note the low-signal edema or tumor, or both, within the fractured vertebra and the other neoplastic foci at the T12 and L3 levels (*arrows*). **B,** T1 sagittal image of the lumbar spine with IV contrast. Note the diffuse enhancement of the fractured vertebra and metastatic foci that are now hard to distinguish from adjacent marrow. **C** , T1 sagittal image of the lumbar spine with IV contrast and fat suppression. There is strikingly increased conspicuity of the enhancing metastatic foci (*arrows*) and fractured vertebra when the fat is suppressed.





FSE-T2W imaging is often combined with frequency-selective fat saturation to highlight areas of soft tissue and marrow pathology because the high signal intensity of fluid and edema is extremely conspicuous against the dark background of suppressed fat. A major problem with frequency-selective fat saturation, however, is the potential for inhomogeneous suppression of fat signal. Because the technique is sensitive to magnetic field inhomogeneities and susceptibility effects, the fat saturation may be incomplete across an imaging volume; this may even result in inadvertent suppression of water signal in these areas. This failure of fat suppression is especially common along curved surfaces, such as the shoulder and ankle, and may result in spurious signal intensity that mimics pathology. This problem can often be identified by noticing the lack of suppression of the overlying subcutaneous fat signal in these regions, but it can be difficult to recognize and may result in diagnostic errors (Fig. 1.18 (f0095)).

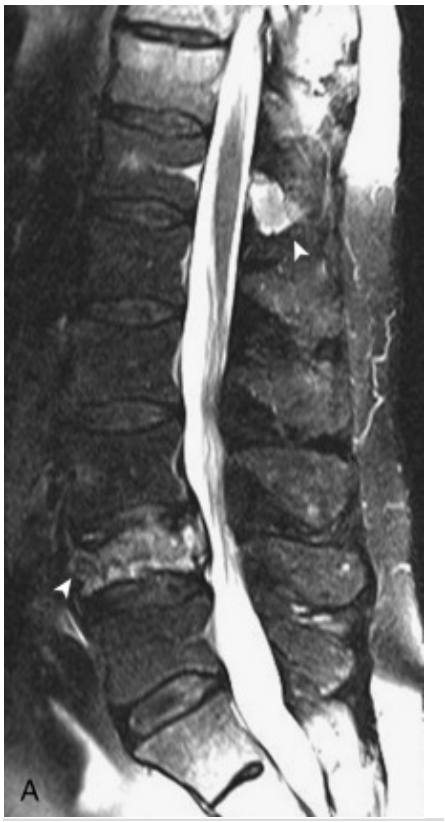
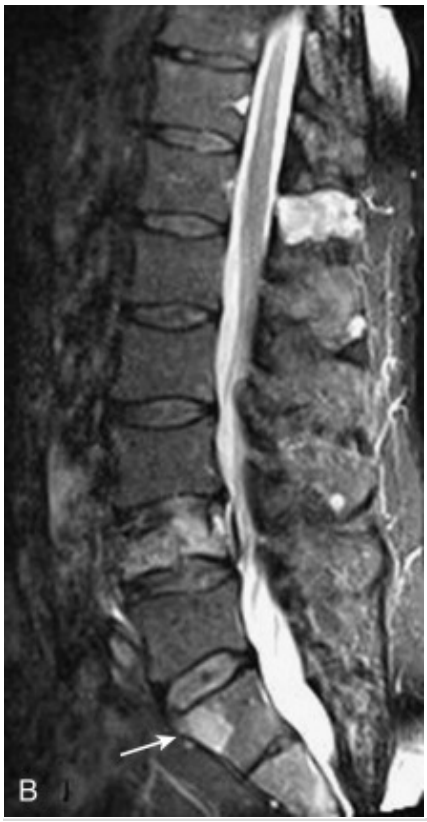


Fig. 1.18

Pitfall: heterogeneous fat saturation. A , FSE-T2 sagittal image with fat saturation of the lumbar spine (same patient as in Fig. 1.17 (f0090)). The high signal intensity within the pathologic burst fracture at L4 and the myelomatous focus in the spinous process of T12 (*arrowheads*) are well shown against the suppressed fat in those regions. Tissues at the superior and inferior margins of the image are not well evaluated, however, due to poor fat saturation in these regions. **B,** STIR sagittal image of the lumbar spine. An additional lesion is detected at S1 as a result of the improved fat saturation obtained with this technique (*arrow*).



Frequency-selective fat saturation relies on adequate separation of the fat and water peaks, which occurs only at high field strengths ($\geq$ 1.0 T). Consequently, another drawback of this technique is that it is not available on mid- and low-field-strength machines.

Inversion Recovery

The inversion recovery (STIR) technique also results in fat saturation, but it is based on the *relaxation properties* of fat protons, rather than their resonant frequency, as is the case with frequency-selective fat saturation. Many clinicians use an FSE-T2W sequence with fat saturation rather than STIR imaging, and although these appear similar in terms of image contrast, there are some differences because the two techniques are based on different mechanisms. First, the STIR technique tends to produce more homogeneous fat suppression because it is not as sensitive to field inhomogeneity as the frequency-selective technique. Second, a STIR sequence should not be used with IV or intra-articular Gd-DTPA

because the contrast agent has similar relaxation properties to fat protons, and its signal intensity would be saturated along with fat on the STIR images.

Gadolinium (Box 1.1) (b0010)

Gd-DTPA is a paramagnetic compound that shows increased signal intensity on T1W images. It has two major routes of administration: IV and intra-articular. Intra-articular use of Gd-DTPA in MR arthrography is discussed in the next section. IV Gd-DTPA should be used only for certain indications, especially in light of more recent reports of an apparent link between Gd-DTPA agents and a rare, but potentially devastating, condition called *nephrogenic systemic fibrosis (NSF)* or *nephrogenic fibrosing dermopathy (NFD)*. This condition is most commonly seen in patients with poor renal function.

BOX 1.1
Gadolinium: When to Use It

- Mass: Cyst versus solid
- Mass: Viable tumor versus necrosis (biopsy guidance)
- Infection: Abscess versus phlegmon
- Spine: Disk herniation versus scar within 6 months of surgery

When administered via IV, Gd-DTPA is analogous to iodinated radiographic contrast agents and results in enhancement proportional to soft tissue vascularity. Contrast enhancement is

more easily evaluated on T1W–fat saturated images. By administering Gd-DTPA *and* applying fat saturation, however, two variables affecting tissue contrast have been changed, and care must be taken to avoid diagnostic errors. As an example, when pre–Gd-DTPA T1W images are obtained *without* fat saturation, a hematoma (higher in signal than muscle) may show apparent enhancement on T1W–fat saturated, postcontrast images, not because of true tissue enhancement, but because the subacute blood products within the hematoma may *appear* brighter because of the suppression of adjacent fat. Ideally, before administering Gd-DTPA, a precontrast fat-suppressed image should be performed.

IV Gd-DTPA is not administered for most musculoskeletal MRI examinations, but it is indicated in certain situations, as follows.

Cystic Versus Solid

Gd-DTPA is useful for distinguishing cystic lesions from cystic-appearing solid masses. A true cyst shows thin peripheral enhancement without enhancement of the cyst fluid centrally (Fig. 1.19 (f0100)). A solid mass shows diffuse enhancement—or at least large areas of enhancement.

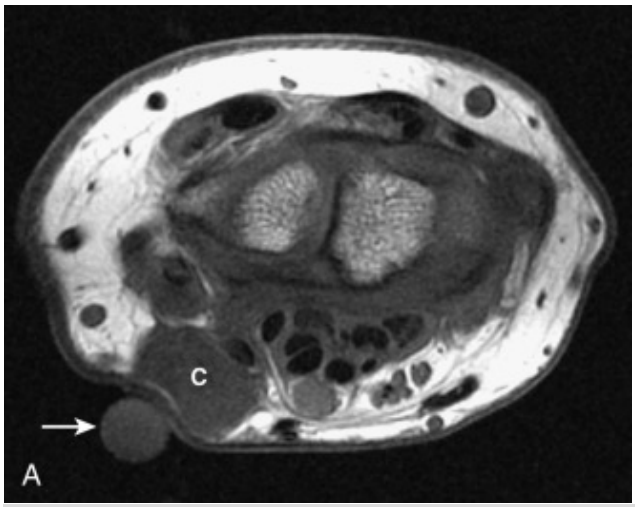
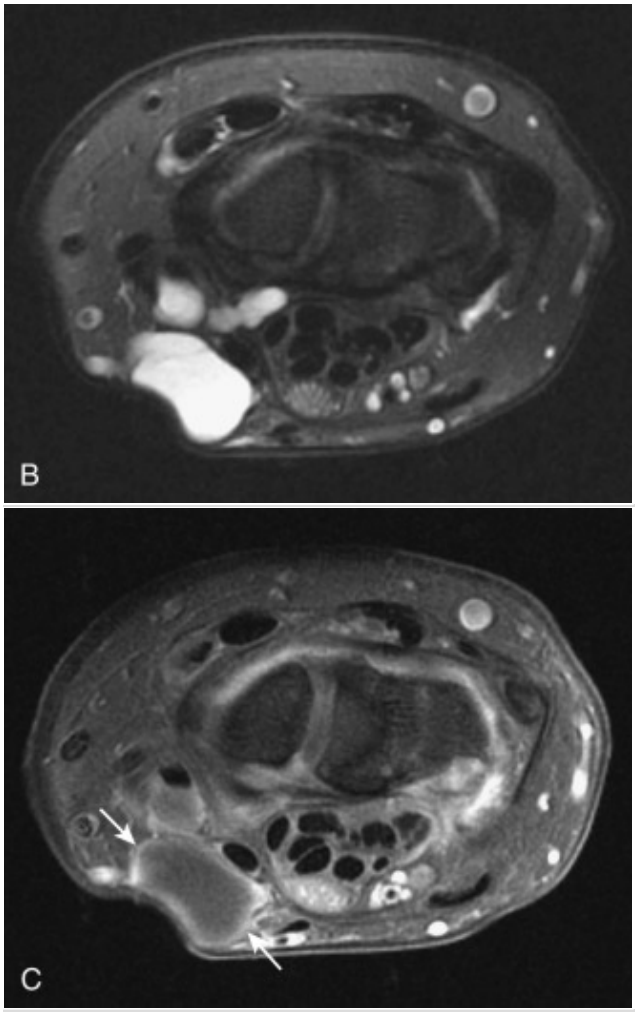


Fig. 1.19

Gd-DTPA: cyst versus solid mass. A , T1 axial image of the wrist. There is a low-signal-intensity mass (C) along the radial aspect of the wrist (*arrow* indicates skin marker). **B,** Fat-saturated T2 coronal image of the wrist. The well-circumscribed mass shows homogeneous, bright signal intensity. **C** , T1 axial image of the wrist after the administration of IV Gd-DTPA. The cystic nature of this ganglion is confirmed by its thin peripheral enhancement (*arrows*) and lack of enhancement centrally.



Tumor

We use Gd-DTPA in the evaluation of soft tissue masses, especially when trying to differentiate cystic from solid lesions. Gd-DTPA can also be helpful in directing a biopsy by differentiating enhancing

viable tumor tissue from areas of nonenhancing necrosis. It is often not helpful in evaluating osseous tumors, but may assist in detecting adjacent soft tissue involvement.

Infection

In cases of soft tissue infection, Gd-DTPA enhancement can assist in differentiating soft tissue edema or phlegmon from a focal abscess, which can be difficult on T2W or STIR images alone. An abscess typically shows a thick enhancing wall and lack of central enhancement. Similarly, small sinus tracts are detected more easily on postcontrast images. Marrow enhancement after contrast administration is a nonspecific finding because it can result from osteomyelitis, as well as areas of noninfected, reactive marrow edema related to hyperemia.

Spine

Gd-DTPA is useful in a postoperative patient for differentiating enhancing scar tissue from nonenhancing disk material. This is primarily true within 6 months of disk surgery. Contrast administration later than 6 months after surgery is not usually as helpful as in the earlier postoperative period for distinguishing retained or recurrent disk from postoperative scar. Contrast Gd-DTPA also is helpful for evaluating cord lesions (e.g., tumor, demyelinating disease) and intradural/extramedullary lesions (e.g., metastases, nerve sheath tumors).

MR Arthrography

Distention of a joint with a solution containing dilute Gd-DTPA is extremely useful for detecting certain types of pathology, such as labral tears in the shoulder and hip. MR arthrography of the knee is

also useful in patients with a history of prior surgery because it allows for differentiating between a meniscal tear (contrast extends into the tear) and scar within a healed meniscal tear. This is considered an “off-label” use by the Food and Drug Administration but has become a commonly used technique in most musculoskeletal imaging practices

We place 0.1 mL of Gd-DTPA into 20 mL of sterile saline immediately before joint puncture. Only this small amount of Gd-DTPA is administered, because if the Gd-DTPA is too concentrated, it will result in a loss of signal from the fluid.

T1W images are sufficient for arthrographic imaging, and fat saturation is often employed to distinguish Gd-DTPA from fat (e.g., in the subacromial/subdeltoid bursa in the shoulder). A T2W sequence in at least one plane also is necessary to detect edema, cysts, or other T2-sensitive abnormalities in the soft tissues or marrow.

Musculoskeletal Tissues

This section is a summary of the appearance of various musculoskeletal tissues on MRI and the sequences we have found most helpful in their evaluation (Table 1.5 (t0030)).

Table 1.5

Musculoskeletal Tissues: Best Sequences

Bone/marrow	STIR	Fast T2 With Fat Saturation	T1

Bone/marrow	STIR	Fast T2 With Fat Saturation	T1
Cartilage	FSE with fat saturation	STIR	GRE (especially with fat saturation)
Meniscus	Spin echo proton density (± fat saturation)	GRE T2*	T1
Labrum	T1 after intra-articular Gd-DTPA injection	GRE T2*	FSE proton density (± fat saturation)
Tendons/ligaments	Fast T2 (± fat saturation)	STIR	
Muscle	STIR	T1	

GRE , Gradient echo; *STIR* , short tau inversion recovery.

Bone

Normal Appearance

Cortical bone is black on all imaging sequences because protons within the mineralized matrix are unable to resonate and produce signal. Within the medullary cavity, fat and hematopoietic marrow are identified. Hematopoietic marrow is slightly hypointense to fat on T1W images and mildly hyperintense to muscle on all sequences (Fig. 1.20 (f0105)).

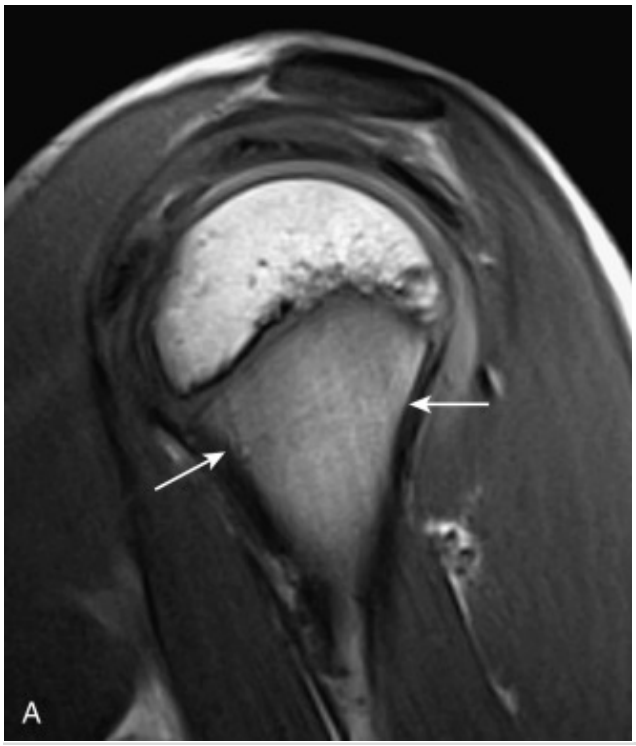
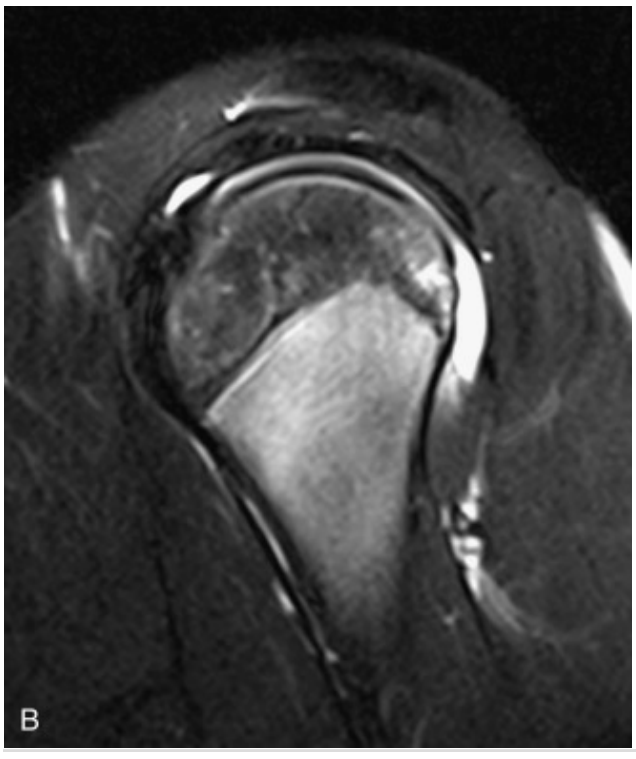


Fig. 1.20

Normal marrow. A , T1 oblique-sagittal image of the proximal humerus. There is intermediate signal intensity within the proximal humeral shaft and metaphysis (*arrows*) that is slightly brighter than skeletal muscle. **B,** STIR sagittal image of the proximal humerus. The hematopoietic marrow is even more conspicuous because of its high signal intensity (related to its cellularity and fluid content) and suppression of the adjacent marrow fat.



Most Useful Sequences

1. *STIR:* Extremely sensitive for detecting subtle marrow pathology.

2. *FSE-T2 with fat saturation:* Sensitivity similar to STIR but may show heterogeneous fat suppression.

3. *T1:* Good for detecting tumors and prominent marrow edema. It is not as sensitive as STIR for subtler pathology, but it is very helpful for further characterizing abnormalities observed on STIR or FSE-T2 with fat saturation.

Pitfalls

1. Marrow pathology may be obscured on FSE-T2W images without fat suppression because of the similar high signal intensity of fat and pathologic lesions on these images.

2. Marrow pathology is easily missed on gradient echo images on high-field-strength machines because of the susceptibility effects of trabecular bone, as described earlier.

Articular Cartilage

Normal Appearance

The normal appearance of articular cartilage varies, depending on the sequence.

Most Useful Sequences

1. *STIR or fat-saturated FSE-T2:* Cartilage is dark gray and easily distinguished from joint fluid, making focal defects quite conspicuous (Fig. 1.21 (f0110)). The cartilage is difficult to

separate from underlying subchondral bone, but this distinction is less important than identifying abnormalities of the articular surface.

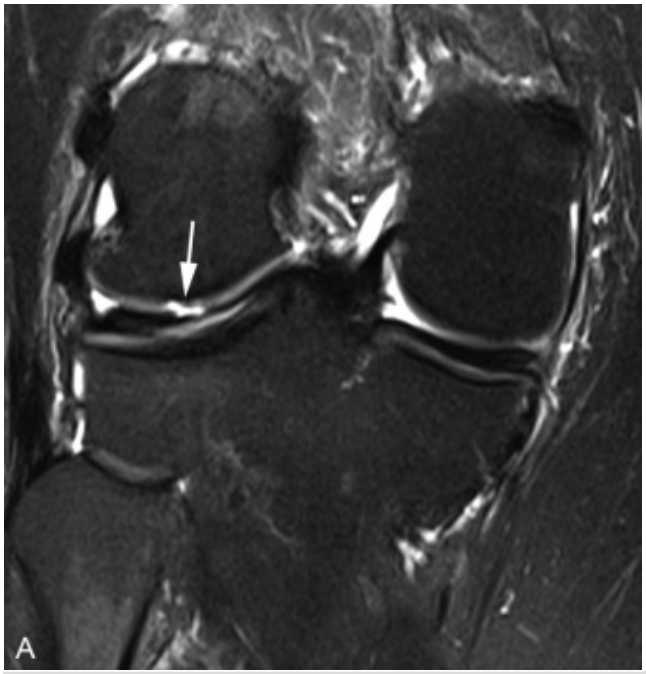
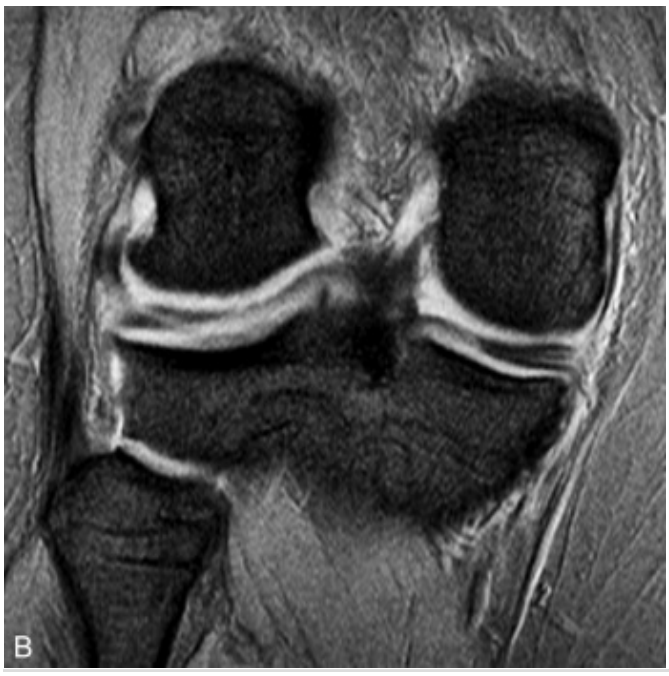


Fig. 1.21

Focal cartilage defect. A , Coronal FSE T2-weighted image of the knee with fat saturation. A focal cartilage defect is well demonstrated along the weight-bearing surface of the lateral femoral condyle (*arrow*). **B,** Note the poor conspicuity of the defect on this coronal gradient echo T2* weighted image due to the similar signal intensity of fluid and cartilage.



2. *PD with or without fat saturation:* Best when sequence parameters are used such that fluid is slightly brighter than articular cartilage.

3. *3D–T1W gradient echo with fat saturation:* Cartilage is very bright and easily distinguished from subchondral bone and fluid. Because this sequence is quite time consuming and must be added to the standard imaging sequences (in contrast to a STIR sequence), it is impractical for routine use.

Fibrocartilage

Normal Appearance

Fibrocartilage normally appears dark on all sequences.

Useful Sequences: Meniscus

Meniscal tears are best shown with short TE sequences.

1. FSE PD (with or without fat saturation)

2. Gradient echo T2*

3. T1

Pitfalls

1. Most tears are not seen well with long TE (T2W) images.

2. The inherent blurring artifact of FSE-PD sequences may obscure some meniscal tears if scanning parameters are not optimized as described earlier in the chapter.

Useful Sequences: Glenoid or Acetabular Labrum (Fig. 1.22) (f0115)

1. T1W images after intra-articular Gd-DTPA injection (with or without fat suppression)

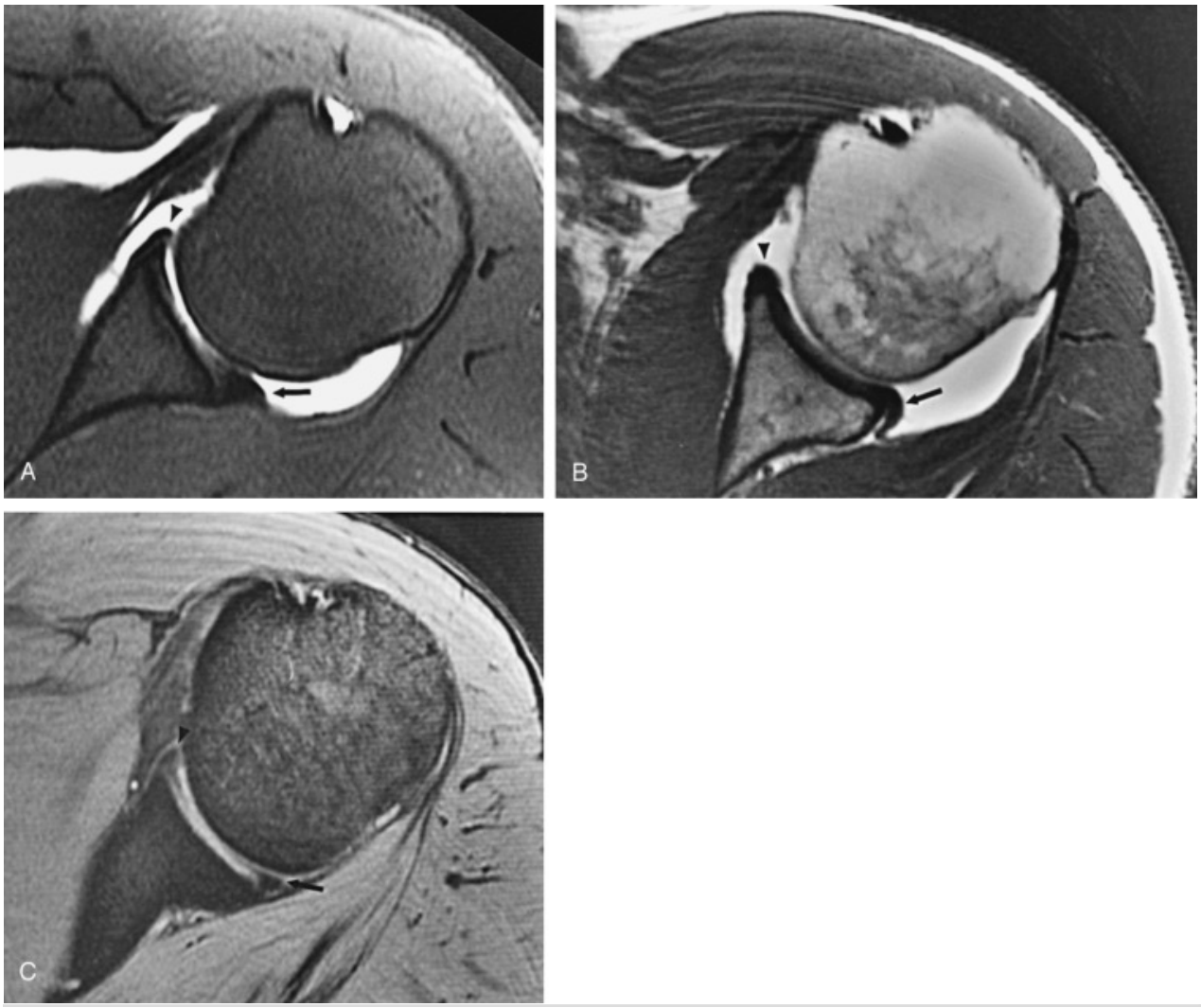


Fig. 1.22

Fibrocartilage: glenoid labrum. A , T1 axial image with fat suppression of the left shoulder after intra-articular administration of dilute Gd-DTPA solution. The anterior labrum (*arrowhead*) and posterior labrum (*arrow*) are well shown, primarily due to the excellent joint distention and contrast between the Gd-DTPA solution and low-signal-intensity labral tissue. Fibrocartilage is normally low signal on all pulse sequences. **B,** T1 axial image of the left shoulder after the intra-articular administration of dilute Gd-DTPA solution. There is better contrast between the low-signal anterior labrum (*arrowhead*) and posterior labrum (*arrow*) underlying bone when fat suppression is not performed. **C** , T2* gradient echo axial image of the left shoulder. The low-signal anterior labrum (*arrowhead*) and posterior labrum (*arrow*) are well shown, but the lack of joint distention limits labral/capsular evaluation overall.

2. FSE PD with fat suppression

3. Gradient echo T2*

Tendons and Ligaments

Normal Appearance

Tendons and ligaments are generally dark on all sequences, with the exception of the anterior cruciate ligament, which shows a striated appearance due to the thickness and orientation of its collagen bundles. The quadriceps and triceps tendons normally have longitudinal striations as well. Some tendons, such as the posterior tibial, show increased signal near their insertions as a result of multiple osseous attachments.

Most Useful Sequences (Fig. 1.23) (f0120)

1. STIR/FSE-T2 with or without fat saturation

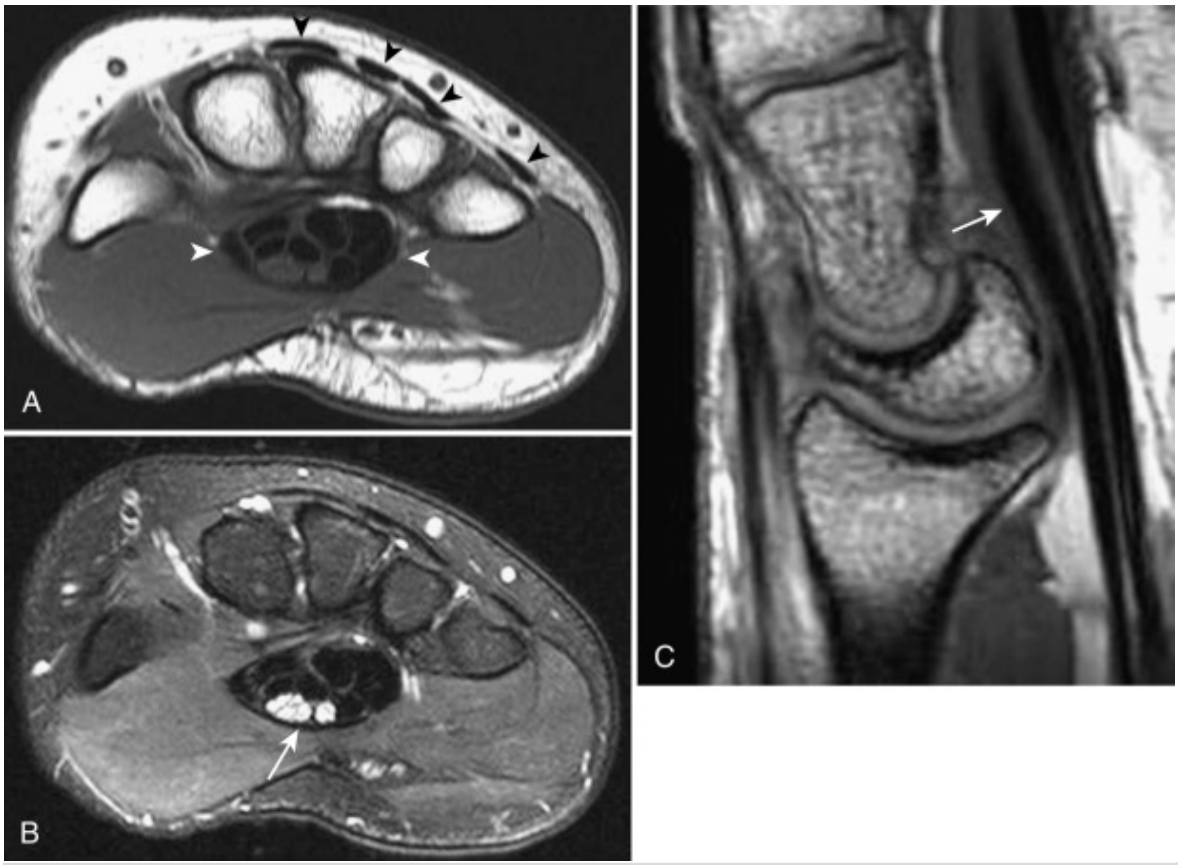


Fig. 1.23

Normal tendons. A , T1 axial image of the wrist. The low-signal flexor tendons are well shown within the carpal tunnel (*white arrowheads*), as are the extensor tendons along the dorsum of the wrist (*black arrowheads*). **B,** FSE-T2 fat-saturated axial image of the wrist. The flexor and extensor tendons remain low signal intensity. Note the high-signal bifid median nerve within the carpal tunnel, a normal variant (*arrow*). **C** , Gradient echo T2* sagittal image of the wrist. The low-signal-intensity flexor tendons are well displayed in the carpal tunnel (*arrow*).

2. Gradient echo T2* (thin section; 3D imaging useful for small ligaments)

3. T1

Pitfalls

Magic angle refers to spuriously increased signal intensity that may occur within any tissue containing highly structured collagen fibers (tendon, ligament, meniscus, labrum), depending on its position within the magnetic field (Fig. 1.24 (f0125)). This magic angle effect is due to the orientation of the collagen bundles and occurs when the structure lies at an angle near 55 degrees to the main magnetic field. The resulting increased signal is seen on images obtained with a short TE (T1, PD, and most gradient echo sequences), but disappears on long TE (T2W) images. This latter feature allows for differentiation from true tendon pathology. Other supportive signs of magic angle include a lack of tendon enlargement or peritendinous edema.

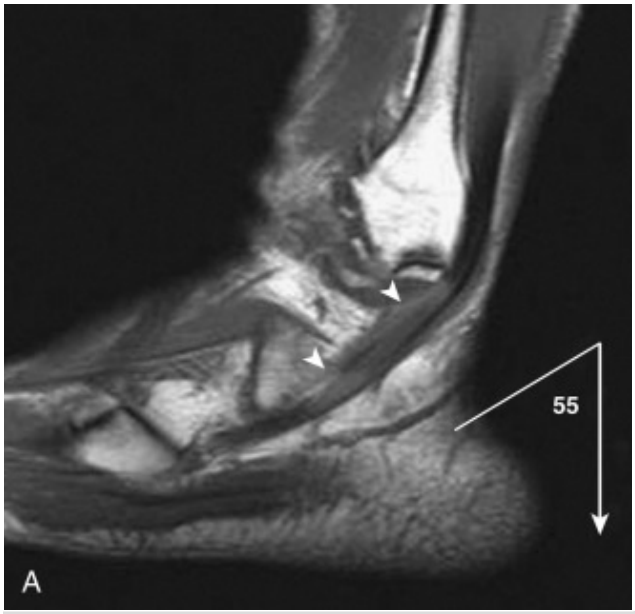
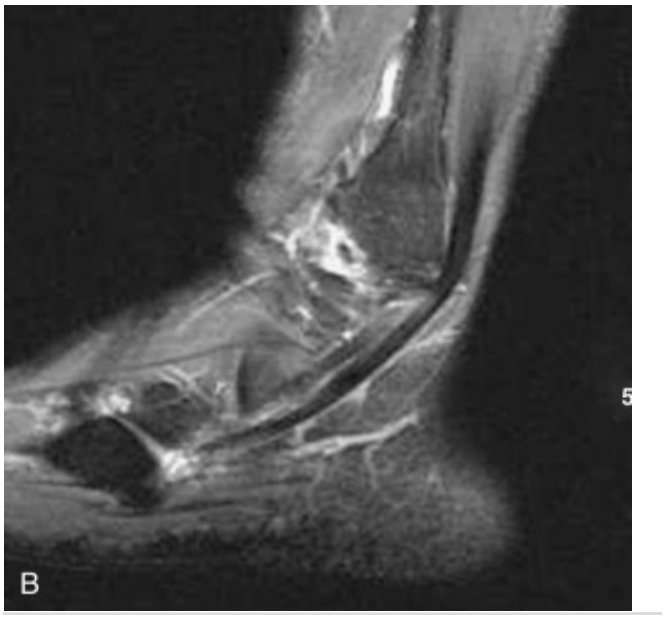


Fig. 1.24

Magic angle artifact. A , Spin echo–T1 sagittal image of the ankle. There is intermediate signal intensity within the peroneus tendons (*arrowheads*), where they course near 55 degrees to the main magnetic field (*arrow* aligned with main magnetic field, B^0). **B,** STIR sagittal image of the ankle. The intermediate signal intensity disappears and the tendons display normal size and low signal intensity.



Muscle

Normal Appearance

The normal appearance of muscle is intermediate signal intensity on all sequences.

Useful Sequences (Fig. 1.25) (f0130)

1. *T1:* Good depiction of overall muscle architecture and of fatty atrophy of the muscle

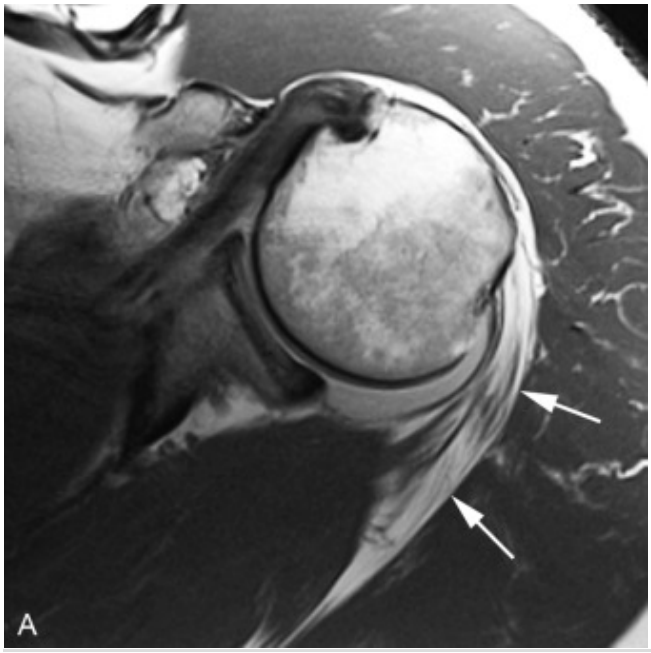
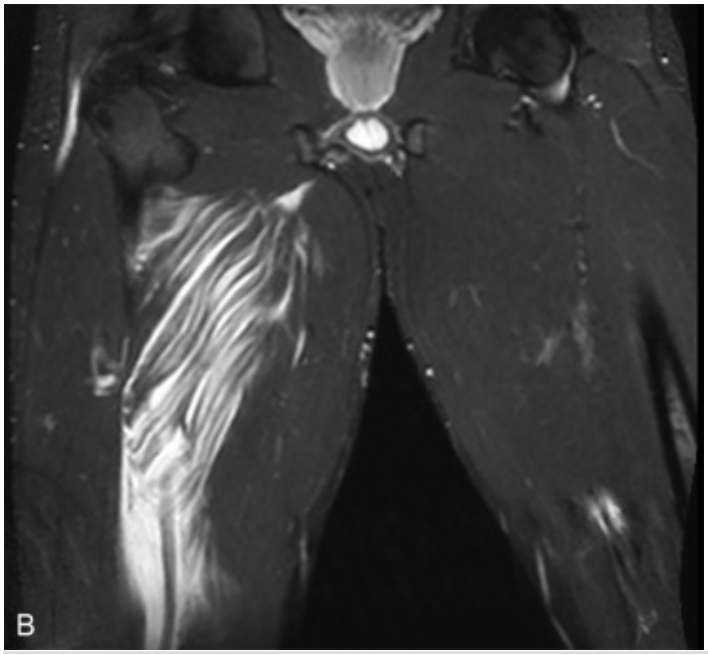


Fig. 1.25

Muscle. A , Axial T1-weighted image from an MR arthrogram of the left shoulder. There is prominent fatty atrophy of the teres minor muscle (*arrows*). Note the normal high-signal-intensity fat striations (“marbling”) of the overlying deltoid muscle, typical of skeletal muscle. B, Coronal STIR image of the thighs demonstrates extensive fluid/hemorrhage in the right hamstring muscles in this college football player who sustained an injury while running.



2. *STIR:* Extremely sensitive for detecting most types of muscle pathology other than atrophy

Synovium

Normal Appearance

The synovium is not usually evident unless it is pathologically thickened.

Useful Sequences (Fig. 1.26) (f0135)

1. T1W fat-saturated images after the administration of IV Gd-DTPA.

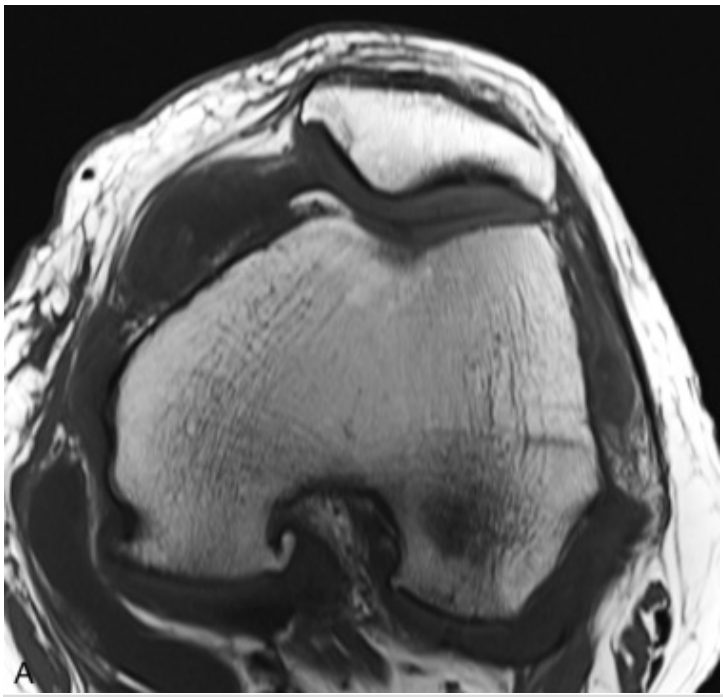
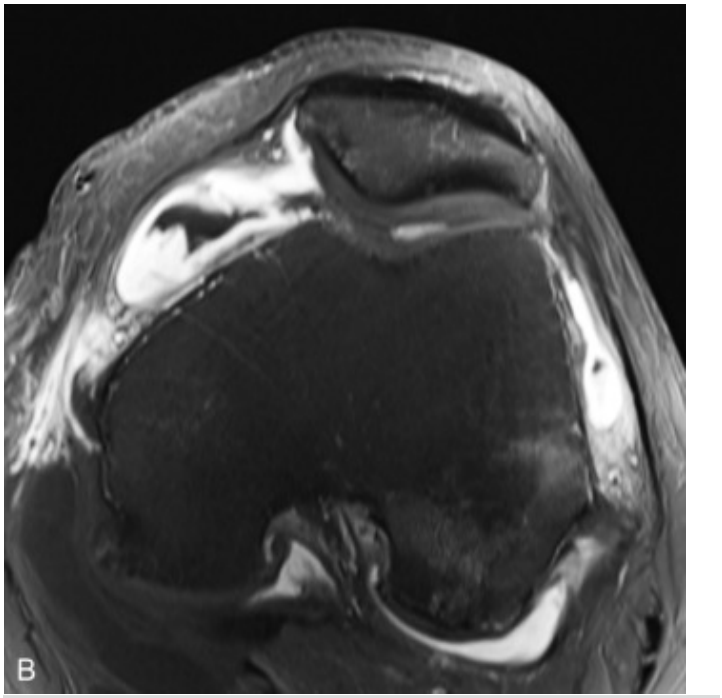


Fig. 1.26

Synovium. A , Axial T1-weighted image of the knee. There is a joint effusion, but the joint fluid is inseparable from synovium. **B,** Axial T1-weighted image with fat saturation after the intravenous injection of gadolinium contrast reveals massive thickening of the enhancing synovium and a relatively small amount of dark, nonenhancing fluid.



2. FSE T2 with or without fat saturation will show the synovium as more intermediate signal, whereas the joint fluid is higher in signal intensity.

3. T1W images without Gd-DTPA enhancement show synovial pannus as intermediate-signal-intensity tissue that is slightly higher in signal intensity than adjacent joint fluid or muscle. This slightly higher signal intensity can be detected with careful scrutiny of the images but is much less conspicuous than after Gd-DTPA enhancement.

Pitfalls

It is not always possible to distinguish hypertrophied synovium from joint fluid on T2W and STIR images.

Applications

Because each anatomic site contains multiple different structures within the volume being imaged (e.g., tendons, cartilage, bone, muscle, spinal cord), it is necessary to use protocols that adequately show all of these varied structures. Pulse sequences and imaging planes must be selected carefully to show these structures optimally in a relatively short time. The clinical indications for obtaining an MRI examination further help determine which pulse sequences and imaging planes should be selected. There is no added value in obtaining every pulse sequence or imaging plane known; it would not improve your ability to make a diagnosis compared with using tailored protocols. Clinicians also appreciate the use of standardized protocols because this consistency allows them to become familiar with the anatomy and pathology shown on the studies.

It is hoped that the basic information presented in this chapter regarding MRI as it relates to the musculoskeletal system will allow you to be street smart about MRI without being plagued by details of the physics (unless you want to be). It is our impression that name dropping various MRI terms in front of clinicians serves little to no useful purpose. Our orthopedists are not impressed if they hear us discussing flip angles, TRs, TEs, and signal intensity. They are much more pleased if we point to a white line traversing the black triangle of a meniscus and assure them that they will find a meniscal tear at arthroscopy.

The protocols presented in each subsequent chapter are based on our approach to musculoskeletal MRI. These work well for us, but we recognize that there is more than one way to perform any given MRI examination properly. Our protocols are meant to serve as a useful guide. Because of the different types of equipment available, we cannot specify all of the parameters, such as TR and TE. Instead, we have concentrated on the field of view, section thickness, imaging planes, and pulse sequences used for different indications. The precise TR, TE, number of signal averages, and matrix size would need to be optimized for the particular machine with which you work.

Remember, all scanners are *not* created equal. If you try to duplicate the results from an article written by investigators using one type of MRI scanner by using their protocol on a different brand of scanner, it probably will not work because each machine uses different methods to acquire and display the data. First, you need to work at understanding the fundamentals that go into

producing a high-quality MR image; then work just as hard at understanding how this can be achieved with your particular machine.

Suggested Reading

Physics

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Jacobs M.A., Ibrahim T.S., Ouwerkerk R.: MR imaging: brief overview and emerging applications.RadioGraphics 2007; 27: pp. 1213-1229.

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Weishaupt D., Koechli V.D., Marincek B.: How Does MRI Work? An Introduction to the Physics and Function of Magnetic Resonance Imaging.2006.SpringerBerlin

Nephrogenic Systemic Sclerosis

Broome D.R., Girquis M.S., Baron P.W., et. al.: Gadodiamide-associated nephrogenic systemic sclerosis: why radiologists should be concerned.AJR Am J Roentgenol 2007; 188: pp. 586-592.

Magic Angle

Erickson S.J., Cox I.H., Hyde J.S., et. al.: Effect of tendon orientation on MR imaging signal intensity: a manifestation of the “magic angle” phenomenon.Radiology 1991; 183: pp. 389-392.

GLOSSARY: COMMON TERMS IN MUSCULOSKELETAL MRI

Coil	Piece of hardware that can transmit or receive radiofrequency pulses during MRI. All scanners are equipped with a large body coil within the scanner itself. For most musculoskeletal applications, a surface coil is used. This is a smaller coil that can be placed on or around the body part of interest for improved imaging.
Cross talk	Phenomenon that occurs as a result of some "spillover" of radiofrequency excitation between adjacent tissue slices during MRI and results in increased image noise. This effect can be minimized by inserting small "gaps" of nonimaged tissue between adjacent slices.
Echo	Refers to the radiofrequency returning from tissues, which is used to create the final image. Various types of echoes (e.g., spin echo, gradient echo) are produced, depending on which pulse sequence is used.
Echo train	Specialized rapid pulse sequences can produce a series of echoes, known as an *echo train,* in the same amount of time that conventional sequences produce a single echo. The reduction in imaging time is directly proportional to the length of the echo train (typically 2-16). See also *fast spin echo* .

Fast spin echo (FSE)	Family of pulse sequences that include Rapid Acquisition with Refocused Echoes (RARE), fast spin echo (General Electric term), and turbo spin echo (Siemens/Philips term). These pulse sequences produce images with contrast similar to conventional spin echo sequences but in less time.
Fat saturation	Certain scanning techniques result in the suppression (reduction) of the signal intensity arising from fat. The two main techniques are inversion recovery imaging and frequency-selective (chemical) fat suppression.
Field of view	Amount of tissue included on each cross-sectional image. Typically expressed in mm^2 or cm^2.
Gadolinium	Paramagnetic compound that forms the basis for most MR contrast agents. Its primary effect is to cause increased signal intensity on T1-weighted images within tissues (if administered intravenously) or within a joint (if administered intra-articularly after being diluted in saline).
Gap	Small slice of nonimaged tissue inserted between two adjacent imaging slices to reduce cross talk.

Gradient echo	Family of pulse sequences originally developed to produce T2-weighted images in less time than with the spin echo technique. Because of differences between these two types of sequences, gradient echo–T2W images are designated T2*W and are especially useful for imaging ligaments, fibrocartilage, and hyaline articular cartilage. They also are useful for identifying areas of hemorrhage, metal, bone, or air due to heightened susceptibility effects.
Inversion recovery	Commonly known as *STIR (short tau inversion recovery).* This technique results in excellent fat suppression and high signal intensity from areas of fluid or edema; it is extremely sensitive for detecting many types of acute pathology.
Matrix	Grid of voxels that compose each MR image. Typical matrix values range from 256 × 256 to 512 × 512 (width × height).
Noise	The quality of an MR image is determined largely by two competing factors—signal and noise. Image noise refers to the background graininess that results from several factors, including the background electrical noise of the imaging system, the presence of the patient in the magnet, the imaging coil used, and other factors. For a given patient, the noise is constant, and maneuvers employed to improve the signal of the image result in an improved signal-to-noise ratio (SNR) and a better image.

Proton density sequence	Pulse sequence that is relatively balanced in terms of T1 and T2 weighting (TR < 1000, TE > 30). Tissue contrast on these images is based on the number of protons within each tissue, rather than their T1 or T2 relaxation properties. (Fat is relatively bright, whereas fluid is gray because of the higher number of protons per unit volume in the fat.)
Pulse sequence	Combination of imaging parameters that are selected at the MRI console to produce images of predictable tissue contrast. The most common families of pulse sequences include spin echo, FSE, gradient echo, and inversion recovery (STIR).
Resolution	Ability to distinguish between two objects. The better the resolution of an image, the easier it is to distinguish objects of increasingly smaller size. Generally, the smaller the voxels in an image, the better the resolution, but this also results in decreased image signal.
Signal average	Number of times each portion of tissue (voxel) is sampled to generate an MR image. Increasing the number of signal averages improves the signal-to-noise ratio of an image but also prolongs imaging time proportionately.
Slice thickness	Thickness of the MR image. Although each image is projected two-dimensionally on a monitor or film, it represents a three-dimensional slice of tissue, typically ranging from 1 to 10 mm in depth. The smaller the slice thickness, the better the resolution.
Spin echo sequence	Family of pulse sequences that includes T1-weighted, proton density–weighted, and T2-weighted sequences.

STIR (short tau inversion recovery)	See *inversion recovery* .
Susceptibility	Degree to which a tissue distorts the magnetic field around it. Certain materials, such as surgical hardware, metal fragments, or the iron-containing hemoglobin found within areas of hemorrhage, have large susceptibilities and tend to create artifactual signal loss on MR images. Gradient echo pulse sequences accentuate these artifacts. FSE sequences tend to minimize them.
T1, T2	Inherent properties of tissue that define how a proton will react during MRI. Each tissue has unique T1 and T2 values. As a result, contrast between tissues on an MR image is based primarily on differences in T1 or T2 properties, depending on the imaging parameters selected (i.e., T1 or T2 “weighting”).
TE	Also known as *echo time,* a parameter selected at the imaging console that controls the T2 weighting of an image. A short TE minimizes T2 differences, whereas a long TE maximizes T2 weighting.
TR	Also known as *repetition time,* an imaging parameter selected at the console that controls the amount of T1 weighting in an image. A short TR maximizes T1 differences, whereas a long TR minimizes T1 weighting.
Turbo spin echo	See *fast spin echo* .

Voxel	Basic unit of the MR image, this represents a small portion of tissue within the patient that is sampled during the MR examination. The size of each voxel is determined by the field of view, imaging matrix, and slice thickness. Also known as *volume elements*.
Weighting	Refers to the contrast properties of a particular imaging sequence. This is determined by selecting specific scanning parameters at the console that emphasize contrast differences between tissues based on tissue-specific properties (e.g., T1-weighted or T2-weighted images).

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