A Systematic Approach to Magnetic Resonance Imaging Interpretation of Sports Medicine Injuries of the Knee

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Magnetic resonance imaging is performed more commonly on the knee than on any other joint, and it is an excellent diagnostic tool that can aid in the evaluation of a host of sports-related injuries involving the ligaments, tendons, menisci, osseous structures, and articular surfaces. A thorough evaluation of the images, however, can be a daunting task, as the study often contains dozens of images obtained with multiple pulse sequences and in several imaging planes. A systematic approach will facilitate an accurate and timely evaluation of this complex examination and will ensure that all of the clinically relevant structures are adequately assessed. This article will provide a systematic approach to the interpretation of a magnetic resonance examination of the knee. The normal imaging appearance of each anatomical structure will be described, and the optimal pulse sequence and imaging plane for the evaluation of each structure will be discussed. Finally, the signs of injury will be described and illustrated.

Keywords: knee; magnetic resonance imaging (MRI); sports injury; ligaments; meniscus

Magnetic resonance imaging has become a well-established noninvasive tool that can aid in the evaluation of the entire spectrum of internal derangements of the knee. Although the cost varies considerably across the country, the average cost of knee MRI is on the order of several hundred to more than a thousand dollars. The noninvasiveness of MRI combined with its relatively low cost have led to its acceptance by the orthopaedic community, and MRI of the knee is the most frequently ordered MR examination of the musculoskeletal system. The superb soft tissue contrast and multiplanar capabilities of MRI make it ideal for evaluating suspected injuries of the muscles, ligaments, menisci, tendons, and articular cartilage, as well as in the evaluation of bone contusions, occult fractures, and fluid collections about the knee. Also, MRI is a useful adjunctive tool, which when combined with a good physical examination can provide an accurate assessment of the entire knee and thus guide appropriate therapeutic intervention.

Equipment and techniques for MRI vary widely, and although it is generally accepted that high field strength magnets provide the highest quality images, there has been considerable advancement in the technology of low field strength systems over the past few years, greatly improving their image quality. A circumferential surface coil is mandatory to ensure uniform signal-to-noise across the entire image. Complete assessment of the knee requires that images be obtained in the sagittal, coronal, and axial planes. T2-weighted images using either fast spin-echo techniques with fat saturation or short inversion time inversion recovery (STIR) imaging are typically performed in all 3 imaging planes. The T2-weighted pulse sequences have been referred to as the "pathology" sequences and are best suited for detecting injuries of the muscles, tendons, ligaments, and articular cartilage. They also clearly depict marrow abnormalities such as edema or contusion. T1-weighted or proton density images should be performed in the sagittal and coronal planes. These sequences typically produce the highest signal-to-noise and have been referred to as the "anatomy" images. They are the most accurate for detecting meniscal injuries and can be used in conjunction with the T2-weighted images to enhance the evaluation of the osseous structures. This article will describe a systematic approach to the interpretation of MR examination of the knee, and the optimal imaging planes and pulses sequence will be discussed for each anatomical structure.

LIGAMENTS

Cruciate Ligaments

Anterior Cruciate Ligament

The ACL is commonly injured in athletes, and MRI can be a valuable tool not only in evaluating the status of the ACL

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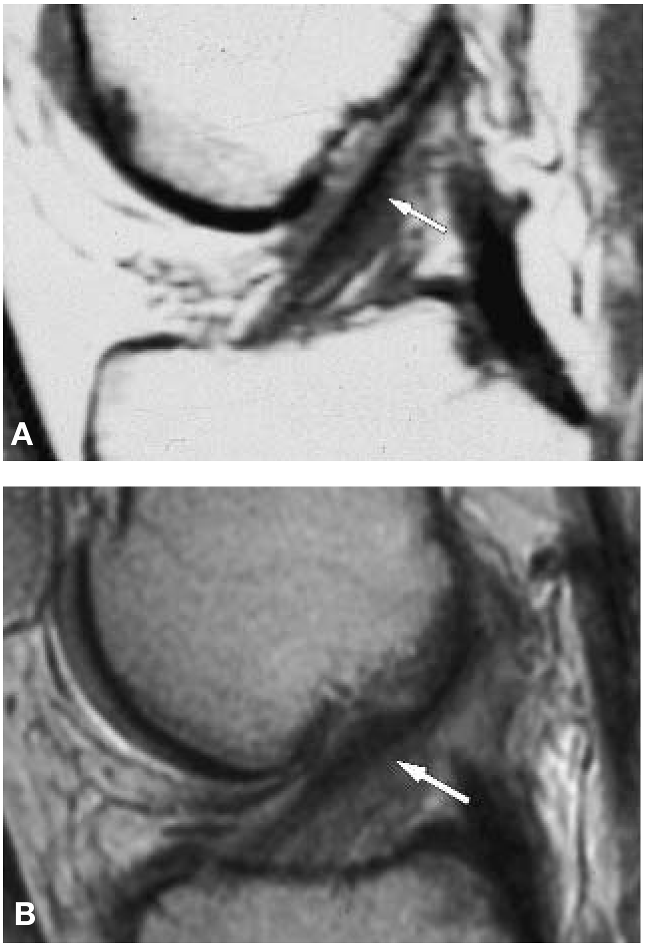

Figure 1. Normal ACL appearance in sagittal plane. The T1-weighted (A) and T2-weighted (B) sagittal images demonstrate the normal ACL (arrows) to be a 3- to 4-mm-thick, dark, band-like structure that parallels the roof of the intercondylar notch (Blumensaat line) but that does not touch the roof.

Figure 2. Normal ACL appearance in axial and coronal planes. A, T2-weighted axial image of the left knee through the level of the intercondylar notch demonstrates the normal appearance of the ACL (arrow) as it arises from the medial aspect of the lateral femoral condyle. Note that on the axial image, the normal ACL has an oval appearance at its proximal attachment site. B, T2-weighted coronal image of the right knee demonstrates the normal striated appearance of the ACL (arrow). The coronal image clearly depicts the proximal and distal attachments.

but also in assessing for associated abnormalities of internal derangement. The accuracy of MRI in the detection of acute ACL disruption ranges from 90% to 95%; however, it is slightly less accurate in depicting partial-thickness tears and chronic ACL-deficient knee conditions.[11,18]

Normal MR Appearance of the ACL

The ACL is composed of 2 separate (anteromedial and posterolateral) bundles. The ligament arises from the medial aspect of the lateral femoral condyle and extends through the intercondylar notch to attach to the tibial plateau adjacent to the anterior tibial spine. With the knee in full extension, the ACL is usually straight but may demonstrate minimal posterior bowing. The proximal ligament appears dark, whereas interspersed fat and synovium between the 2 bundles give the distal ligament a striated appearance that should not be misinterpreted as a tear.

The primary imaging plane for evaluating the ACL is the sagittal plane (Figures 1 A and B), but complete assessment requires a thorough knowledge of its normal appearance in all 3 planes. Axial and coronal (Figures 2 A and B) images are especially helpful in evaluating the femoral attachment, whereas the coronal plane is also complementary in the evaluation of the midsubstance and tibial attachment. The integrity of the ligament is best assessed on T2-weighted or proton density images.

Direct MR Signs of ACL Disruption

- Discontinuity of fibers (Figures 3 A and B).
- Abnormal slope of ACL (Figure 4).
- Nonvisualization of the ACL fibers on both sagittal and coronal planes (Figure 5).
- Avulsion of the anterior tibial spine (Figure 4).

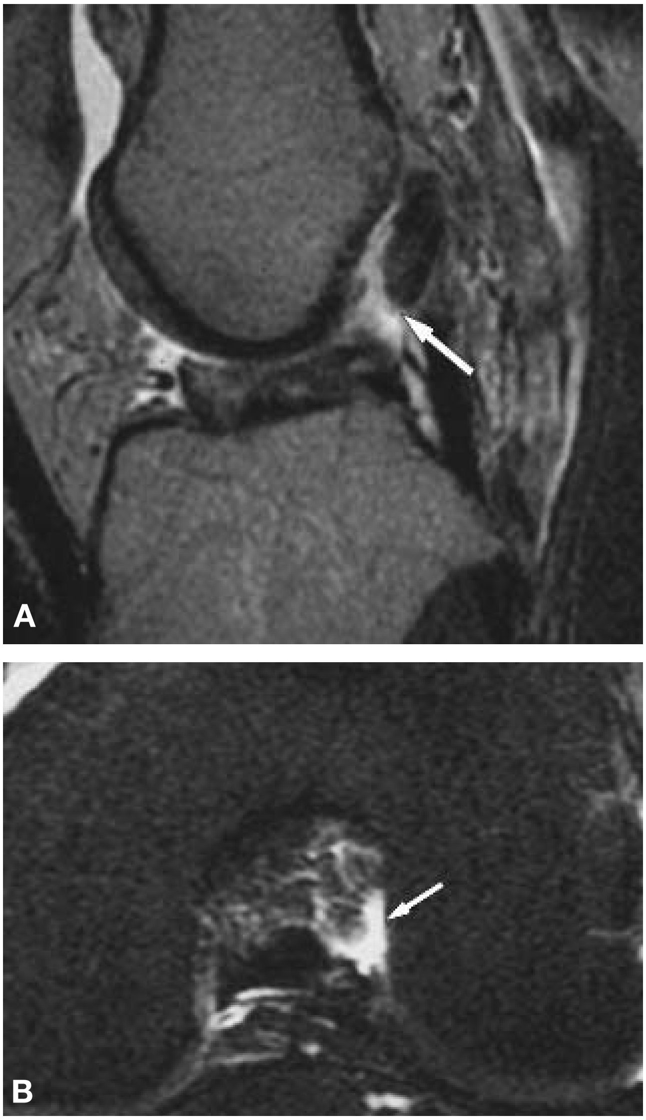

Figure 3. Disrupted ACL. A, T2-weighted sagittal image demonstrates complete disruption (arrow) of the ACL in its midsubstance. B, T2-weighted axial image of the left knee demonstrates the "empty notch" sign—fluid signal intensity in the expected location of the proximal ACL. The axial view can be very helpful in demonstrating avulsion of the ACL from its proximal femoral attachment. See Figure 2 for normal appearance of the ACL femoral attachment.

Although in most instances the direct MR signs of ACL disruption are conclusive, they are occasionally equivocal.[24,30] When equivocal, certain indirect MR signs can increase the level of confidence in detecting an ACL tear. Most indirect MR signs are related to osseous injuries that occur at the time of ACL injury.

Indirect MR Signs of ACL Disruption

- Bone contusion sign: lateral femoral condyle and posterior tibial plateau (pivot-shift injury) (Figures 6 A and B).

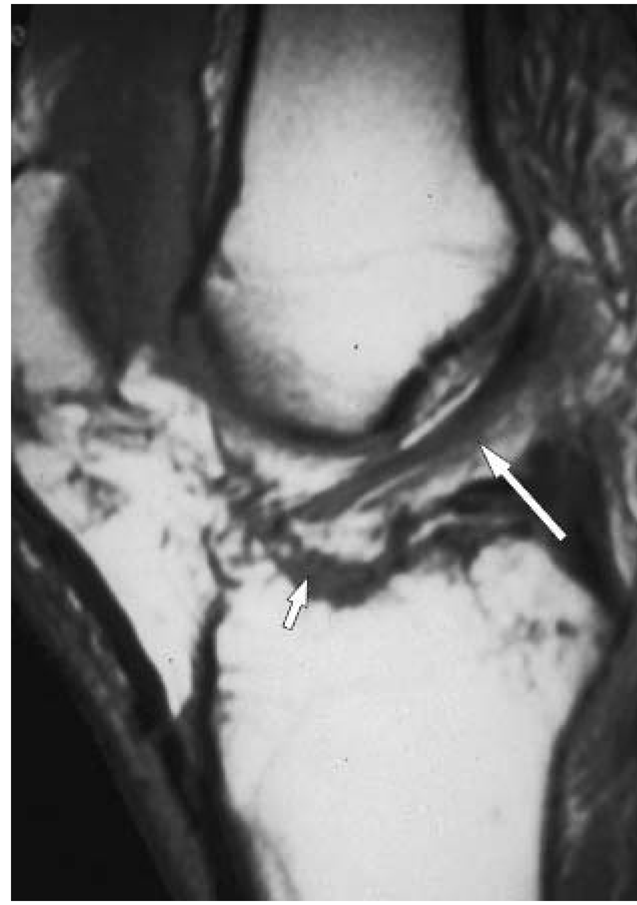

Figure 4. Abnormal slope ACL/tibial avulsion injury ACL. T1-weighted sagittal image demonstrates an abnormal slope (long arrow) with posterior bowing of the ACL. An avulsion fracture (short arrow) of the tibial attachment site of the ACL is also shown.

- Deep sulcus sign: lateral femoral condyle (more than 2-mm deep) (Figure 7).
- Segond fracture: capsular avulsion fracture of the lateral tibial plateau (Figure 8).
- Kissing contusions: anterior tibia and femur (hyperextension injury).
- Anterior drawer sign: anterior translation of tibia relative to femur.
- Buckling of PCL: nonspecific.
- Acute hemarthrosis: nonspecific.

Commonly Associated Soft Tissue Injuries

Soft tissue injuries commonly associated with ACL disruption include tears of the posterior horn of either the medial or lateral meniscus, medial collateral ligament (MCL) injuries, and posterolateral capsular injuries.

Posterior Cruciate Ligament

The PCL is approximately twice as strong and twice as thick as the normal ACL is. The PCL is less commonly

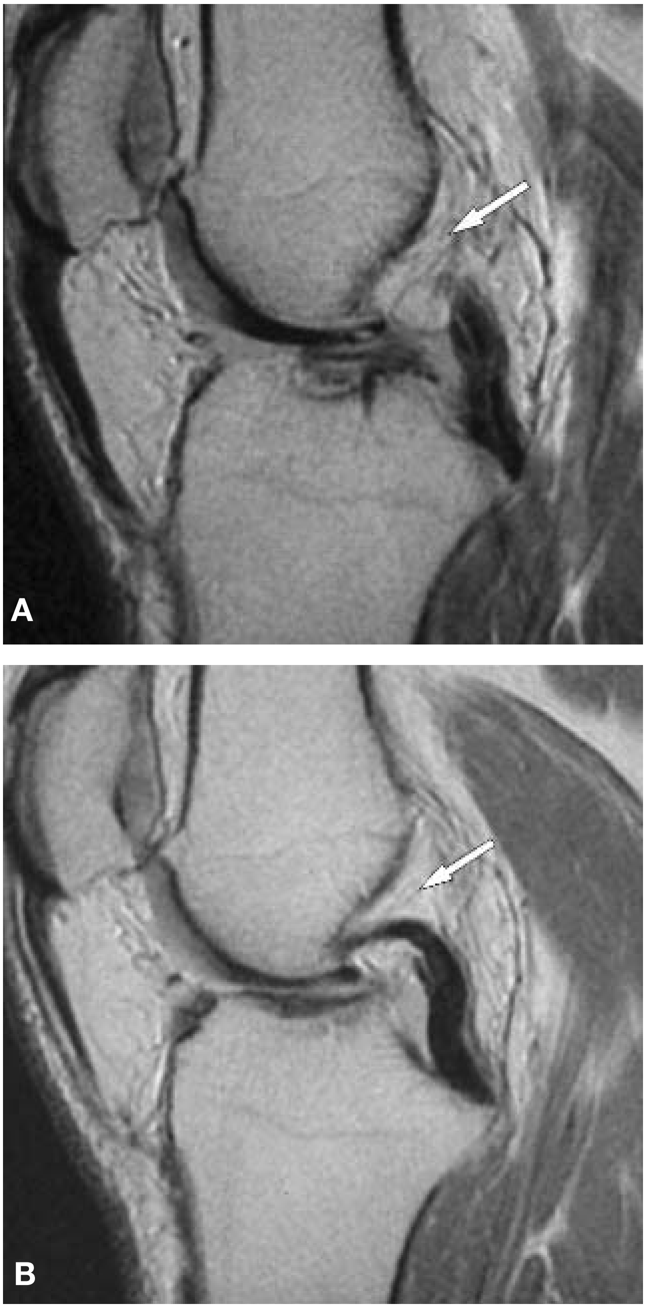

Figure 5. Absent ACL. A, B, consecutive T1-weighted sagittal images through the intercondylar notch demonstrate absence (arrows) of normal fibers in the expected location of the ACL. This is diagnostic of a chronic ACL-deficient knee condition.

injured than the ACL is, but it is more likely to suffer a partial tear of the ligament; MRI is accurate in depicting the entire spectrum of PCL injuries.[9,10,29]

Normal MR Appearance of the PCL

The PCL is best evaluated on the T2-weighted sagittal images and is typically visualized in its entirety on a single image or more commonly on 2 consecutive sagittal images (Figures 9 A and B). Axial and coronal planes are complementary but rarely necessary in the evaluation of the PCL.

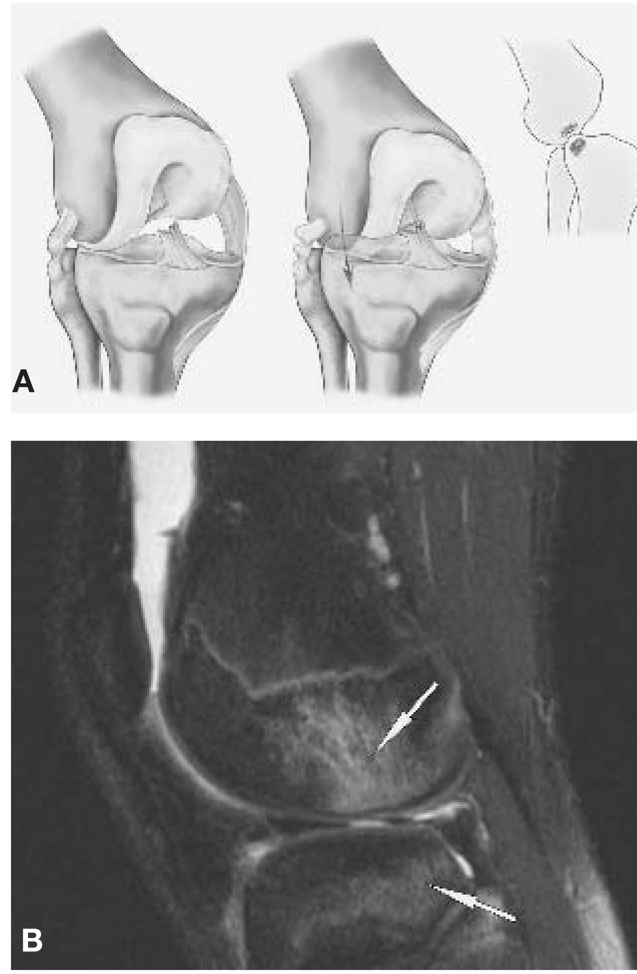

Figure 6. Pivot-shift marrow edema pattern. A, the relationship between the tibia and femur during the pivot-shift injury. As the femur rotates internally, the tibia translates anteriorly, and the lateral femoral condyle impacts the posterior lateral tibial plateau, often resulting in marrow edema in these areas. (Adapted and reprinted with permission from Radio Graphics 20 Spec No: S135-151) B, T2-weighted sagittal image demonstrates the "pivot-shift" bone marrow edema pattern (arrows), which is seen as focal areas of high signal intensity within the otherwise dark marrow. This pattern of edema nearly always results from impaction of the lateral femoral condyle against the posterior tibial plateau and has a very high specificity for ACL disruption.

Primary Signs of PCL Injury

- Complete tear: high signal completely traversing the fibers of the PCL on T2-weighted images (most commonly occurs in the midsubstance) (Figure 10B).
- Partial tear: high signal incompletely traversing the fibers of the PCL on T2-weighted images (Figure 11A).

Figure 7. Deep sulcus sign. T2-weighted sagittal image demonstrates the deep sulcus sign, an impaction injury of the lateral femoral condyle that results from the impaction of the femoral condyle against the posterior tibial plateau during the pivot-shift injury. The sulcus must measure at least 2 mm deep to be considered abnormal.

Figure 8. Segond fracture. T1-weighted coronal image of the left knee demonstrates a Segond fracture, a capsular avulsion fracture (arrow) of the lateral tibial plateau. This fracture correlates highly with a tear of the ACL. An ACL tibial avulsion is also present in this case.

- “Peel-off” injury: an avulsion injury of the femoral insertion of the ligament. This can sometimes result in a small fleck of bone being avulsed off the femur. This injury differs from a midsubstance tear and may be repairable by reattaching the femoral ligament to the medial femoral cortex.

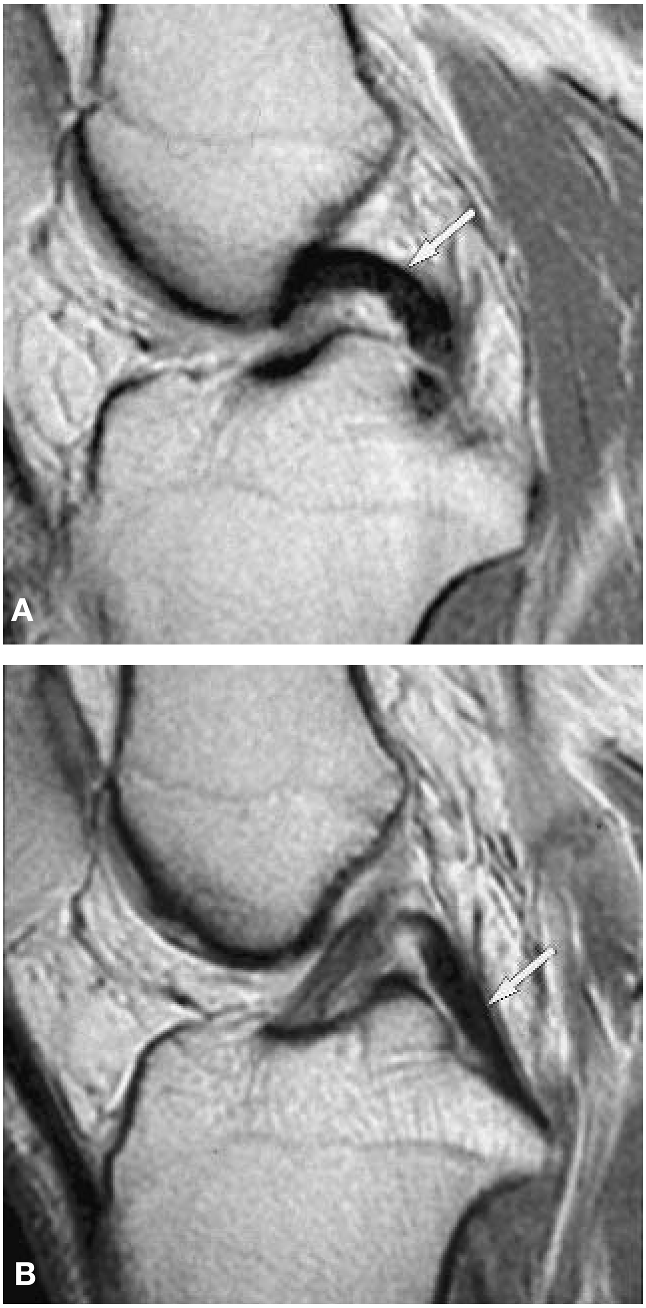

Figure 9. Normal MR appearance of the PCL. A, B, consecutive T2-weighted sagittal images demonstrate the normal PCL (arrows) as a thick, arcuate-shaped, band-like structure of low intensity that extends from the intercondylar portion of the medial femoral condyle to the posterior sloping aspect of the tibial plateau.

Secondary Signs of PCL Injury

- Bone marrow edema (BME) involving the anterior proximal tibia (Figures 10 A and B).
- Avulsion of the posterior tibia at the PCL insertion site (Figures 11 B and C).

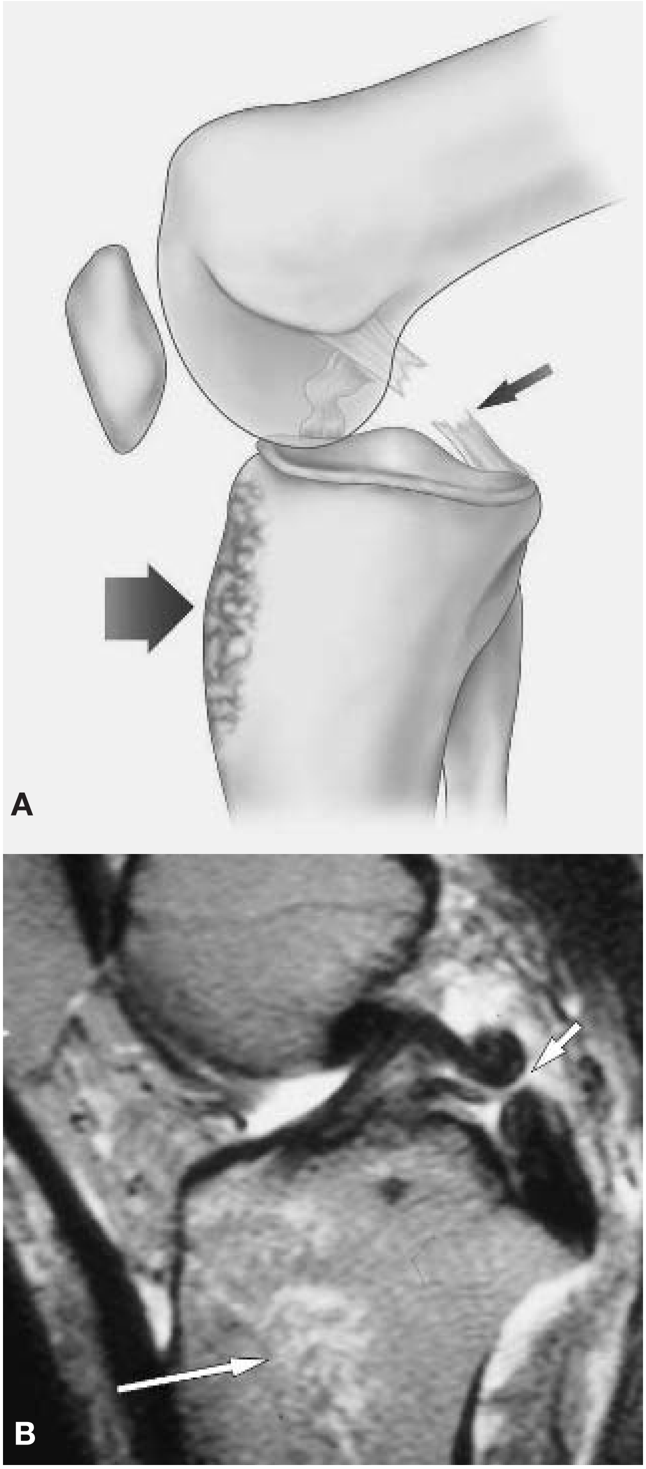

Figure 10. Disrupted PCL with dashboard marrow contusion pattern. A, line drawing demonstrates the dashboard mechanism of injury. This occurs when the knee strikes an object such as a dashboard while the knee is flexed. It results in marrow contusion of the proximal anterior tibia and is often associated with injury of the PCL. B, T2-weighted sagittal image demonstrates complete disruption (short arrow) of the PCL in its midsubstance. Bone marrow edema (long arrow) is seen as high signal within the anterior aspect of the proximal tibia. (Adapted and reprinted with permission from Radio Graphics 20 Spec No: S135-151).

Associated Soft Tissue Injuries

- Disruption of the ACL (in hyperextension mechanism of injury).
- Associated injury of MCL more common than in lateral collateral ligament (LCL).
- Associated injury of medial meniscus more common than in lateral meniscus.

Cruciate Cysts

Cruciate ligaments are intracapsular structures that are enveloped within a fold of synovium. Ganglia originate from the synovial lining of the ACL or PCL and appear on either the surface (Figures 12 A and B) or within the substance of the ligament (Figure 12C). Large cysts can extend into the joint posteriorly, extend into the Hoffa fat pad anteriorly, or occasionally erode into adjacent bone. Cruciate cysts may be identified incidentally on MRI, or they may cause the symptoms of catching, locking, or pain. The cysts are usually well defined, septated, and oval or lobular in appearance, and they follow water signal on all pulse sequences. A cruciate cyst arising on the surface of the ligament may mimic a meniscal cyst, whereas one arising within the substance of the cruciate ligament can mimic a cruciate ligament tear on MRI.[12]

Collateral Ligaments

Normal Anatomy of the MCL

The collateral ligaments are best evaluated on the T2-weighted coronal images of the knee. The MCL is composed of 2 layers: (1) the deep fibers that attach to the capsule and the medial meniscus and (2) the superficial fibers. The tibial collateral bursa is a potential space between the 2 layers. This can sometimes become inflamed and filled with fluid. The MCL is 8 to 10 cm in length and extends from the medial femoral condyle to insert 4 to 5 cm below the joint line on the medial tibia, posterior to the attachment of the pes anserine tendons (Figure 13A).[3,28]

Grading MCL Injuries

- Grade 1 (sprain): edema (fluid signal intensity) superficial to the fibers of the ligament on T2-weighted images (Figure 14A). The fibers of the ligament are intact.
- Grade 2 (partial tear): fluid signal extends partially through the ligament; however, some fibers remain intact (Figure 14B).
- Grade 3 (complete tear): complete discontinuity of the fibers with surrounding edema (Figure 14C).

Associated Abnormalities

Anterior cruciate ligament and meniscal tears can occur in conjunction with MCL injuries. The bone marrow edema may be present in the lateral femoral condyle secondary to direct impact on the lateral femur at the time of the valgus injury. Occasionally, minimal edema may be present in the medial femoral condyle secondary to avulsion of the MCL fibers.

Figure 11. PCL injury patterns. A, T2-weighted sagittal image demonstrates high signal within the midsubstance of the PCL; however, some fibers remain intact. This is consistent with a partial-thickness tear (arrow). B, C, T2-weighted sagittal and coronal images of the left knee demonstrate an avulsion fracture (arrows) of the posterior tibial plateau at the insertion site of the PCL.

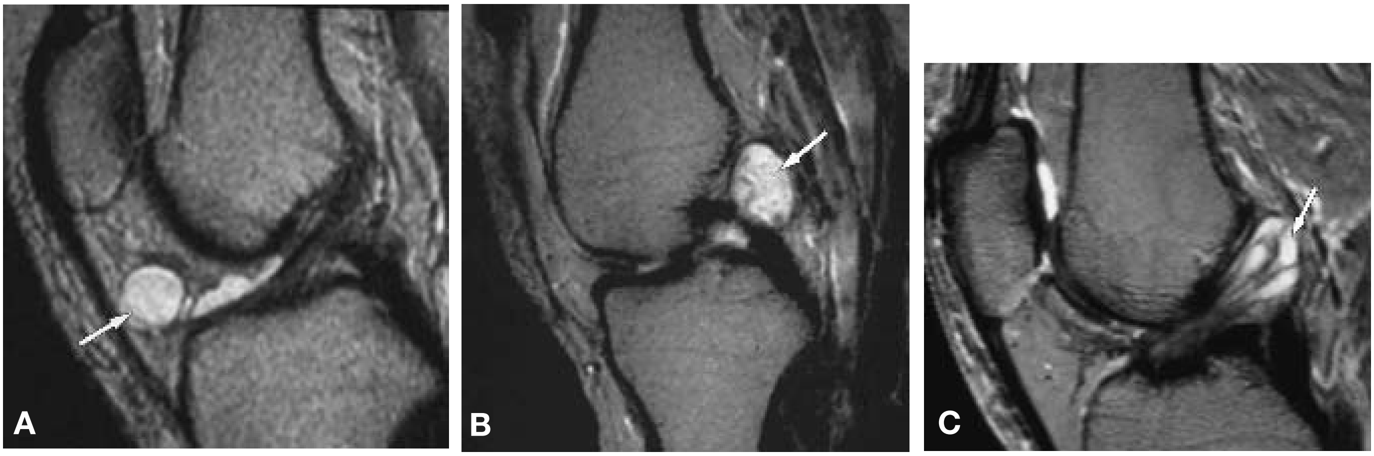

Figure 12. Cruciate cysts. A, T2-weighted sagittal image demonstrates a cruciate cyst (arrow) arising from the anterior surface of the ACL and extending into the infrapatellar fat pad. B, T2-weighted sagittal image in a different patient demonstrates a cruciate cyst arising from the PCL. C, T2-weighted sagittal image demonstrates a cruciate cyst arising within the substance of the ACL. This type of cruciate cyst splays and displaces the fibers of the ACL and can mimic a tear of the ACL.

Figure 13. Normal MR appearance of the collateral ligament complexes. T1-weighted coronal images demonstrate (A, right knee) the normal MR appearance of the medial collateral ligament (long arrow) and iliotibial band (short arrow), (B, left knee) normal fibular collateral ligament (arrow), and (C, left knee) normal biceps femoris tendon (arrow).

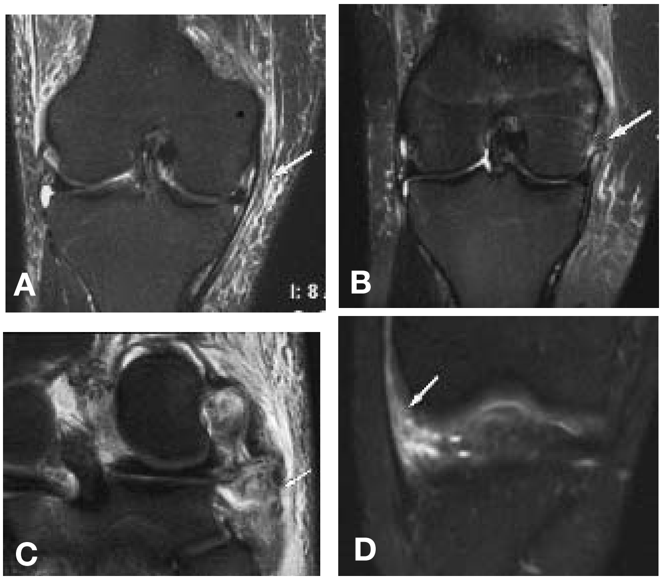

Figure 14. Collateral ligament injuries/iliotibial band syndrome. A, T2-weighted coronal MR image of the right knee demonstrates a grade 1 injury of the medial collateral ligament (MCL) with edema (arrow) superficial to the ligament; however, the fibers remain intact. A medial soft tissue contusion will occasionally mimic a grade 1 injury of the MCL; however, once fluid signal is seen within the substance of the MCL, it is considered a grade 2 injury. B, T2-weighted coronal MR image of the right knee demonstrates a grade 2 partial-thickness tear (arrow) of the MCL. There is partial disruption of the MCL; however, some fibers remain intact (on images posterior to those seen on this image). C, T2-weighted image of the left knee demonstrates a grade 3 injury, with complete disruption (arrow) of the fibular collateral ligament. The fibers are retracted and wavy in appearance. D, T2-weighted coronal image of the right knee demonstrates soft tissue edema (arrow) located deep to the iliotibial band, consistent with iliotibial band syndrome.

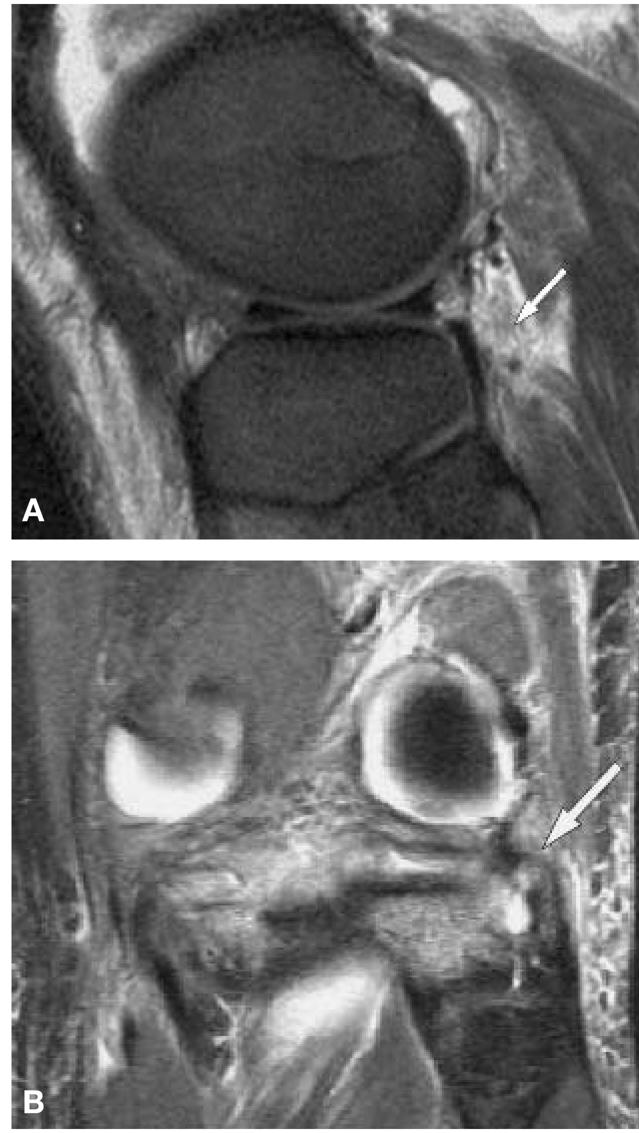

Figure 15. Posterolateral corner injury. T2-weighted (A) sagittal and (B) coronal images of the left knee in a patient with an ACL tear demonstrate extensive soft tissue edema adjacent to the posterolateral corner structures, consistent with posterolateral corner injury.

Normal Anatomy of the LCL Complex/ Posterolateral Corner Complex

The LCL complex is composed of several individual structures: (1) the fibular collateral ligament (Figure 13B) extends from the lateral femoral condyle to the fibular head, (2) the biceps femoris tendon (Figure 13C) merges with the fibular collateral ligament to attach on the fibular head as a conjoined tendon, and (3) the iliotibial band (Figure 13A), an extension of the tensor fascia lata, attaches on the anterior tibia.[23]

Grading LCL Complex Injuries

Injuries of the LCL complex are described using the same 3-point grading system as described above for the MCL.

Associated Abnormalities

Injuries associated with the LCL injury include medial tibial plateau compression fractures resulting from the varus injury. Tears of the iliotibial band, popliteus, and posterior capsule structures may also occur.

Posterolateral Corner Injuries

The posterolateral corner of the knee is anatomically complex and includes the posterior capsule, arcuate ligament, popliteofibular ligament, and the popliteus tendon. Injury to one or more of these structures can result in posterolateral pain, buckling into hyperextension during weightbearing, or instability of the knee on clinical examination. The posterolateral corner is best evaluated on T2-weighted axial and sagittal images (Figures 15 A and B).[14,33] The popliteofibular ligament is located deep to the lateral limb of the arcuate ligament, originating along the posterior

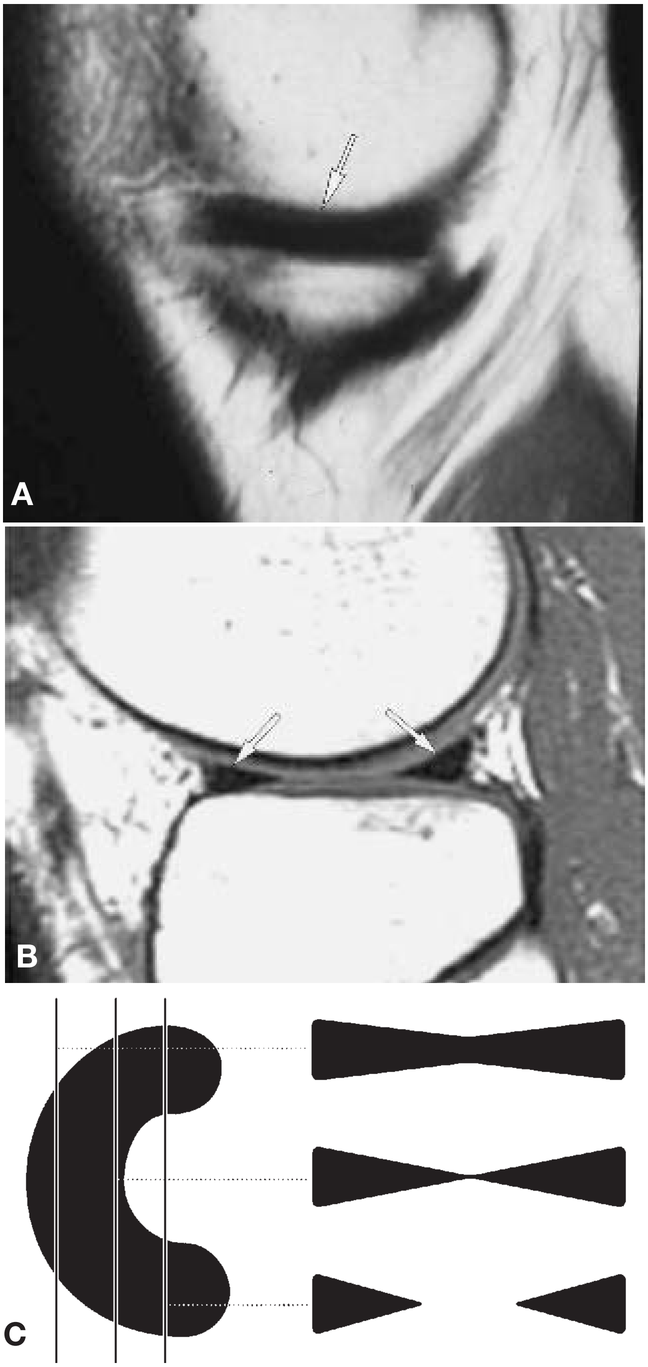

Figure 16. Normal appearance of the meniscus in the sagittal plane. A, T1-weighted sagittal image demonstrates the normal bow tie configuration (arrow) of the peripheral meniscus. B, T1-weighted sagittal image through the more central aspect of the meniscus demonstrates the normal triangular appearance of the anterior and posterior horns (arrows). C, line drawing demonstrates the appearance of sagittal MR images of the meniscus.

aspect of the fibula. From there, it extends to the junction of the musculotendinous junction of the popliteus and then to the femur. It is best evaluated on T2-weighted sagittal or coronal images at the level of the posterior knee.

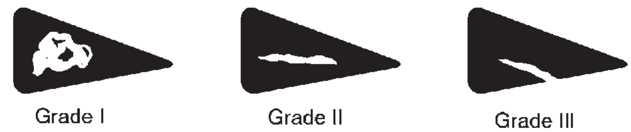

Figure 17. Intrasubstance signal of the meniscus. Grade 1 intrasubstance signal is globular in appearance and does not intersect the superior or inferior articular surface. This does not represent a tear. Grade 2 intrasubstance signal is linear in appearance and does not intersect the superior or inferior surface. This does not represent a tear. Grade 3 signal intersects either the superior or inferior articular surface of the meniscus and represents a tear. Grade 1 or 2 signal represents either intrasubstance degeneration in an adult or prominent vascularity in a child, whereas a grade 3 signal represents a tear.

Signs of Posterolateral Corner Injury

- Visible disruption of one of the posterolateral capsule structures.
- Extensive surrounding soft tissue edema.
- Avulsion fracture or marrow edema involving the medial aspect of the fibular head.

Menisci

Meniscal injury is the most common indication for arthroscopic surgery of the knee, and MRI has evolved into a valuable tool for the preoperative evaluation of the menisci. The accuracy of MRI for detecting meniscal injury ranges between 90% and 95%, and it has been shown that the level of experience of the image reader is the most important factor in obtaining the highest level of accuracy.[4,8,18,20,22,25] A thorough understanding of the normal MR appearance, signs of injury, and anatomical pitfalls of the meniscus is essential if one is to maximize diagnostic accuracy.[5]

Normal Anatomy and MR Appearance

The normal menisci are composed of fibrocartilage and are therefore dark on all pulse sequences.[2] Menisci must be evaluated on both the sagittal and coronal images. The most peripheral images of the sagittal plane demonstrate a "bow tie" appearance of the meniscus (Figure 16A). The normal meniscus should have 1½ to 2 bow ties. More centrally, the meniscus becomes triangular in appearance (Figures 16 B and C). The anterior and posterior horns of the lateral meniscus are nearly equal in size, whereas the posterior horn of the medial meniscus is nearly twice the size of the anterior horn.[17] The signal within the substance of the meniscus is graded as follows (Figure 17): grade 1, intrasubstance globular-appearing signal that does not extend to an articular surface; grade 2, intrasubstance linear signal that does not extend to an articular surface; and grade 3, intrasubstance signal that extends to either the superior or inferior surface. Grades 1 and 2 represent intra-

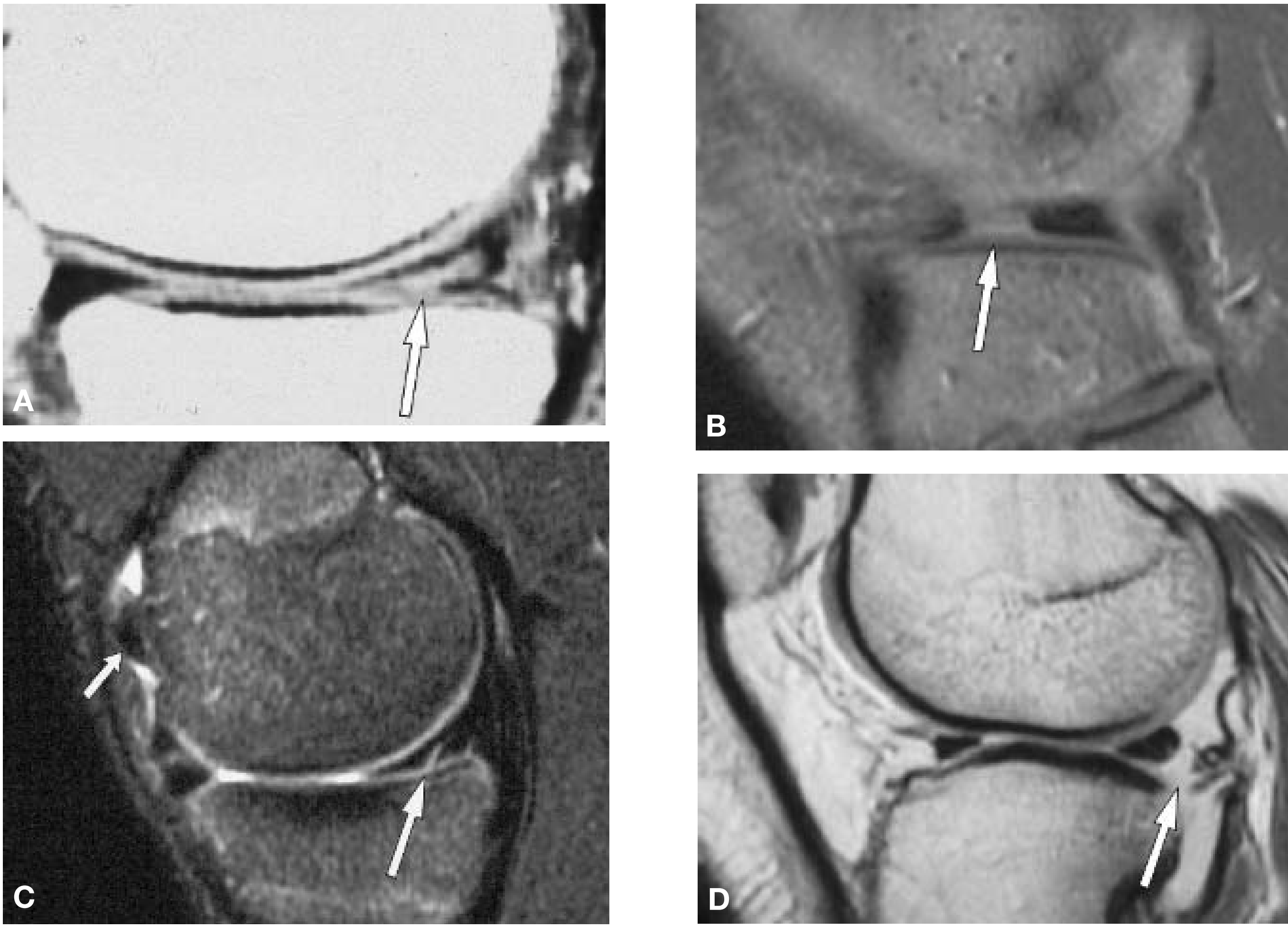

Figure 18. Four direct signs of meniscal tear. A, T1-weighted sagittal image demonstrates grade 3 signal (arrow) intersecting the inferior articular surface of the meniscus. B, T1-weighted sagittal image demonstrates a missing fragment (arrow), which represents abnormal meniscal morphology. C, T2-weighted sagittal image demonstrates an anteriorly displaced meniscal fragment (short arrow). Note the grade 3 signal (long arrow) in the posterior horn. D, T2-weighted sagittal image demonstrates disruption of the meniscal struts (arrow) that connect the posterior horn of the lateral meniscus to the capsule, referred to as a meniscocapsular separation.

substance degeneration in an adult or prominent vascularity in a child—not a tear. Grade 3 signal represents a tear.[18]

Meniscal Tears

Short echo time sequences (T1 or proton density) are most sensitive for identifying meniscal tears. Long echo time (T2) sequences are less sensitive but more specific.[18]

Criteria to Detect Meniscal Tears (Figure 18). (1) Unequivocal grade 3 signal, (2) abnormal meniscal morphology, (3) displaced or missing meniscal tissue in the absence of surgical history, and (4) meniscocapsular separation.

The MRI Signs Associated With Meniscal Tears

- Absent bow tie sign (1 or fewer): bow ties on the most peripheral images of the knee associated with missing meniscal tissue—either postsurgical or displaced tear (Figure 19A).
- Double PCL sign: displaced bucket-handle tear of the medial meniscus (Figure 19B).
- Large anterior horn sign: displaced bucket-handle tear of the lateral meniscus (Figure 19C).
- Too many bow ties (3 or more): discoid meniscus (Figure 20).
- Notch sign: small notch out of the articular surface of the meniscus—high association with tear.

Pitfalls for Detecting Meniscal Tears

- Normal anatomical structures in close proximity to meniscus can mimic a tear. The anterior transverse ligament mimics a tear of the anterior horn lateral meniscus (Figure 21). The meniscofemoral ligaments mimic a tear of the posterior horn lateral meniscus (Figure 22). The medial and lateral oblique menisco-meniscal ligament mimics a bucket-handle tear. The popliteal tendon and bursa mimic a tear of the posterior horn lateral meniscus (Figures 23 A and B).

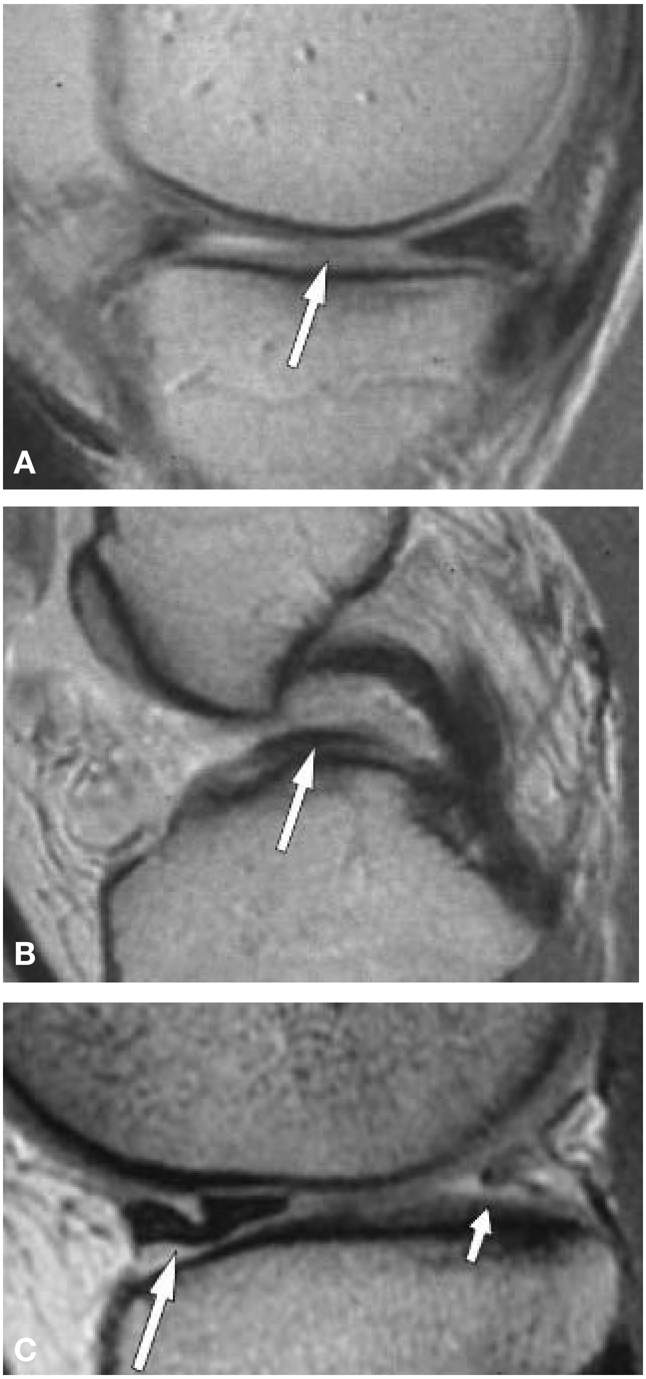

Figure 19. Imaging signs associated with meniscal abnormalities. A, T1-weighted sagittal image demonstrates the "absent bow tie" sign (arrow). The most peripheral sagittal image demonstrates lack of continuity between the anterior and posterior horn of the medial meniscus because the free edge of the meniscus has been torn and displaced into the notch. B, T1-weighted sagittal image on the same patient as (A) demonstrates the "double PCL" sign (arrow). The additional tissue in the notch represents a torn, displaced bucket-handle tear. C, T1-weighted sagittal image demonstrates the "large anterior horn" sign (long arrow). This represents an anteriorly displaced bucket-handle tear of the lateral meniscus. Note that the posterior horn is absent (short arrow).

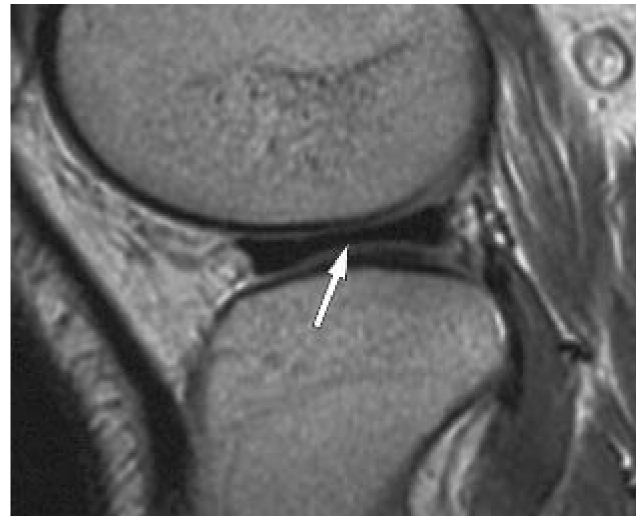

Figure 20. Discoid meniscus. Proton density sagittal image through the lateral meniscus demonstrates continuity between the anterior and posterior horns of the lateral meniscus. This has been referred to as the bow tie configuration. The presence of 3 or more bow ties on the same examination is indicative of an enlarged (discoid) meniscus.

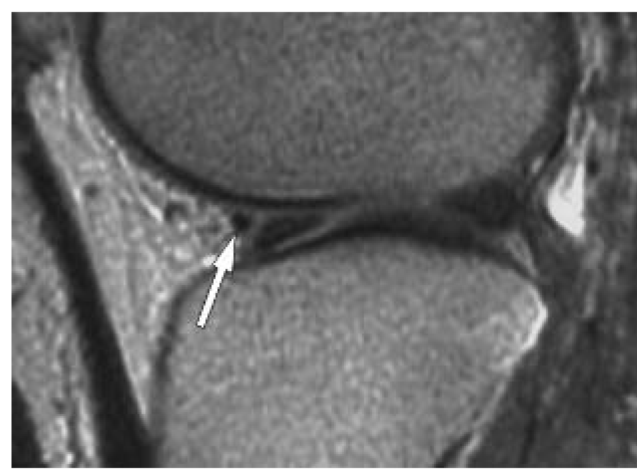

Figure 21. Transverse meniscal ligament. T2-weighted sagittal image demonstrates the anterior transverse meniscal ligament (arrow). On sagittal images, it can mimic a grade 3 signal as it attaches to the anterior horn of the lateral meniscus.

- The MR artifacts can mimic a meniscal tear: volume averaging of adjacent bright structures (fat, fluid); truncation artifact (occurs at high-contrast boundaries) causes alternating high-signal bands that can mimic a tear; motion artifact (can result in blurring of intrameniscal signal, which will subsequently appear as grade 3 signal—if any motion is seen on images, a grade 3 signal should be viewed with suspicion and images repeated if possible); magic angle phenomenon (in curved central portion of posterior horn lateral meniscus).
- Pathologic conditions may mimic a meniscal tear. Gas within the joint (vacuum phenomenon or iatrogenic) can appear as a signal void and mimic a displaced

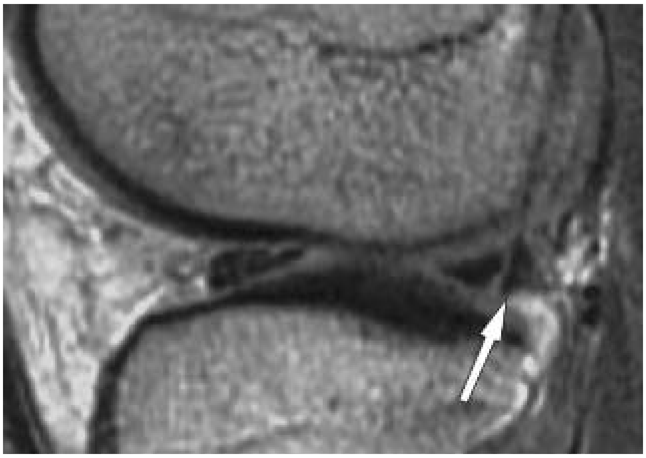

Figure 22. Meniscofemoral ligament. T1-weighted sagittal image demonstrates the normal appearance of the meniscofemoral ligament (arrow) as it arises from the posterior horn of the lateral meniscus. This ligament can mimic a grade 3 signal at its attachment site on the posterior horn of the lateral meniscus.

meniscal fragment. Chondrocalcinosis in meniscus appears bright on MR T1-weighted images; comparison with a conventional radiograph of the knee will help avoid this pitfall. Articular cartilage defects may mimic a meniscal tear and may mimic a displaced fragment.

Postoperative Meniscus

- Grade 3 signal on T1-weighted images only is indeterminate for tear: it may represent postoperative change or retear of the meniscus (Figures 24 A and B).
- Grade 3 signal on a T1-weighted image that is bright as fluid on a T2-weighted image is diagnostic of retear.
- A displaced meniscal fragment is diagnostic of retear.
- Grade 3 signal in new a location is diagnostic of retear (grade 3 signal located remote from prior surgical site; must have accurate surgical history to know what part of meniscus was operated on).

In the postoperative meniscus, routine MR of the knee will prove the meniscus to be either normal or definitely torn in approximately 65% of cases; the remaining 35% of cases will fall into the indeterminate category, using the above criteria, and will require either follow-up arthroscopy or MR arthrography. Magnetic resonance arthrography is approximately 90% sensitive and specific for retear of the postoperative meniscus. Criteria for a retear of the meniscus using MR arthrography are (1) gadolinium intensity signal tracking into the meniscus (Figures 25 A and B) and (2) visualization of a displaced meniscal fragment.[15,31] The authors prefer the use of direct MR arthrography for the evaluation of the postoperative meniscus; however, it is an acceptable practice to begin with conventional MRI in the postoperative setting and reserve MR arthrography for those patients whose conventional MR examinations are indeterminate for a meniscal tear.

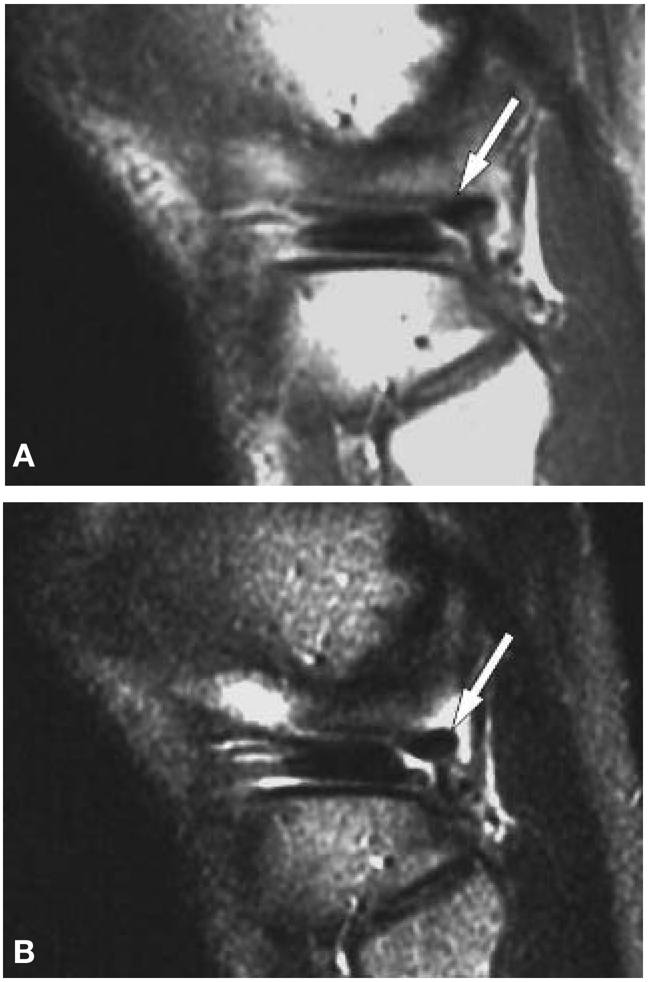

Figure 23. Popliteus tendon. T1-weighted (A) and T2-weighted (B) sagittal images demonstrate the normal appearance of the popliteal tendon (arrows) as it traverses posteriorly to the lateral meniscus. The popliteus tendon can mimic a grade 3 signal.

Meniscal Cyst

A meniscal cyst is a contained fluid collection in the soft tissues adjacent to the meniscus, which results from extrusion of fluid through a tear. It is almost always associated with a horizontal cleavage tear of the meniscus. On MRI, it appears as a lobulated, fluid-filled mass that demonstrates intermediate signal intensity on T1-weighted images and bright signal on T2-weighted images, usually in direct contact with the adjacent meniscal tear (Figure 26).[1]

OSSEOUS STRUCTURES AND ARTICULAR SURFACES

Normal Anatomy

The normal marrow signal about the knee is bright on T1-weighted images and dark on T2-weighted images with fat

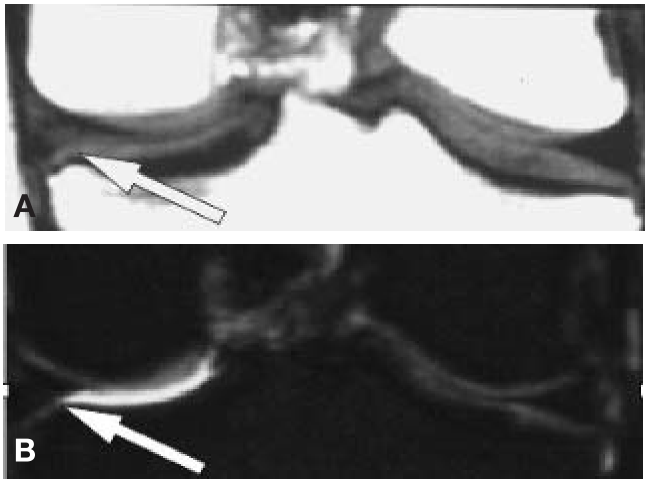

Figure 24. Postoperative meniscus. A, T1-weighted coronal image of the left knee demonstrates grade 3 signal (arrow) extending to the inferior articular surface in a patient with a history of prior partial medial meniscectomy. B, T2-weighted coronal image of the left knee demonstrates absence of grade 3 signal (arrow). This, combined with the findings in (A), is indeterminate for tear and may represent either postoperative change or a retear of the meniscus. Follow-up arthroscopy in this case had negative results for tear, and the grade 3 signal seen only on the T1-weighted images represented postoperative change.

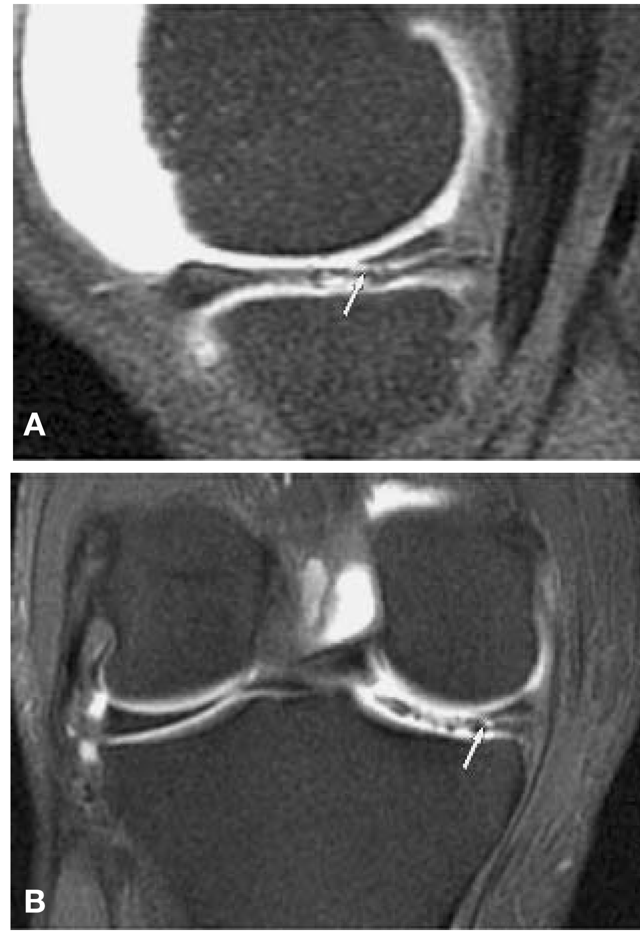

Figure 25. Recurrent tear of a postoperative meniscus on MR arthrogram. T1-weighted sagittal (A) and coronal (B) images of the right knee on a direct MR arthrogram demonstrate contrast (arrows) extending into the substance of the meniscus, consistent with a recurrent tear.

Figure 26. Meniscal cyst. T2-weighted coronal image of the right knee demonstrates a horizontal cleavage tear (long arrow) and a large adjacent meniscal cyst (short arrows). The meniscal cyst is a fluid-filled, lobulated structure that typically has low signal intensity on T1-weighted images and high signal intensity on T2-weighted images.

saturation. Also, MRI is very specific for detecting abnormalities of the bone marrow. In sports-related injuries, the majority of marrow abnormalities seen on MRI represent BME secondary to trauma (Figures 27 A and B).[26] Other possibilities include fracture, tumor, infection, and avascular necrosis. A fracture will appear as a dark line on both T1- and T2-weighted images.

Bone Marrow Contusion Patterns and Associated Soft Tissue Abnormalities

- Pivot-shift injury: BME in the lateral femoral condyle and posterior tibial plateau is associated with ACL disruption (Figure 8).
- Dashboard injury: BME in the anterior proximal tibia is associated with PCL injury (Figures 10 A and B).
- Hyperextension injury: “kissing” contusion pattern of the anterior tibia and femur is associated with tears of the ACL and/or PCL.

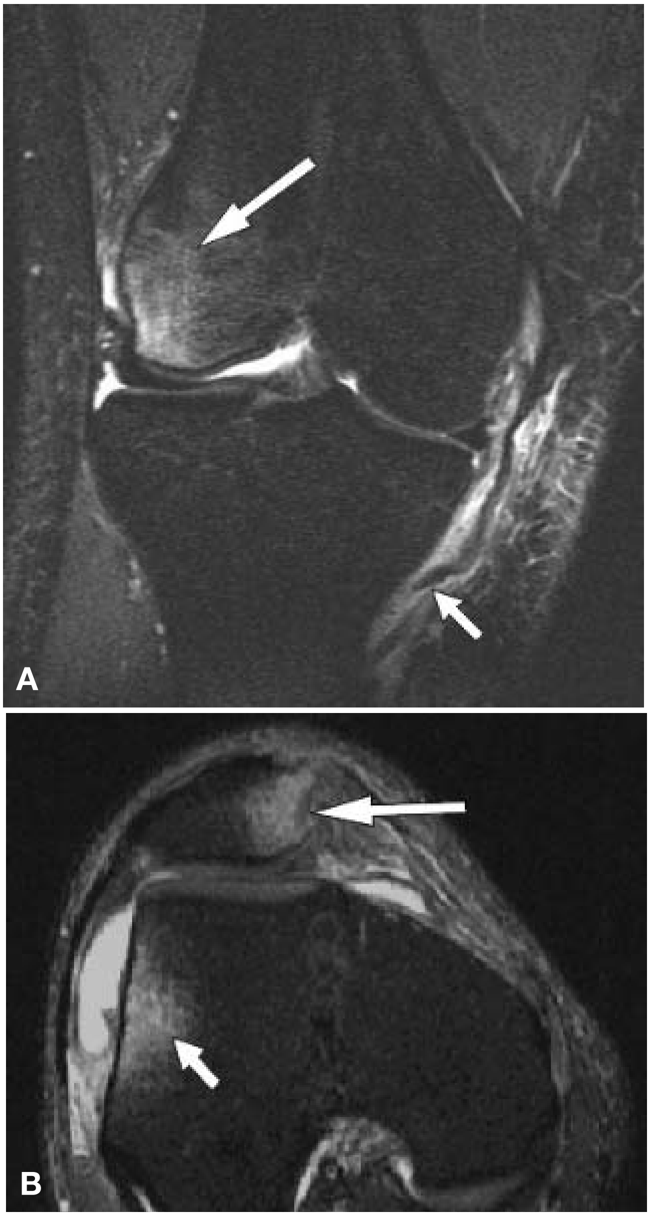

Figure 27. Bone marrow edema patterns. A, T2-weighted coronal image of the right knee demonstrates bone marrow edema (long arrow) in the lateral femoral condyle. This pattern of marrow edema often results from a "clipping"-type mechanism of injury and is associated with injury of the medial collateral ligament (short arrow). B, T2-weighted axial image from a different patient demonstrates marrow edema in the medial patellar facet (long arrow) and lateral femoral condyle (short arrow). This marrow edema pattern occurs after transient dislocation of the patella and is often the first indication that the patient experienced patellar dislocation.

- Clip injury: BME in the lateral femoral condyle resulting from direct trauma is associated with MCL injury (Figure 27A).
- Lateral patellar dislocation: BME in the inferomedial patella and anterolateral aspect of the lateral femoral

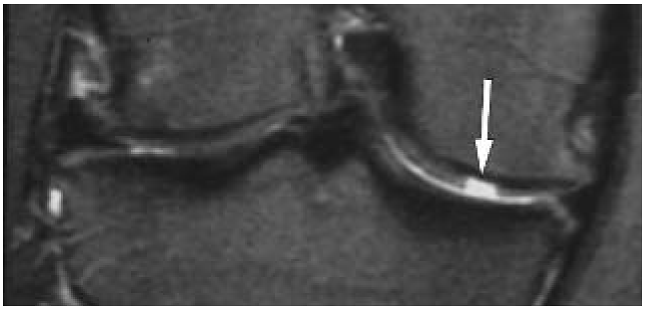

Figure 28. Articular cartilage defect. T2-weighted coronal image of the right knee demonstrates a full-thickness defect (arrow) of the medial femoral condyle articular cartilage. On a fat-saturated T2-weighted image, the normal articular cartilage is intermediate in signal intensity, the cortex is black, and fluid is bright.

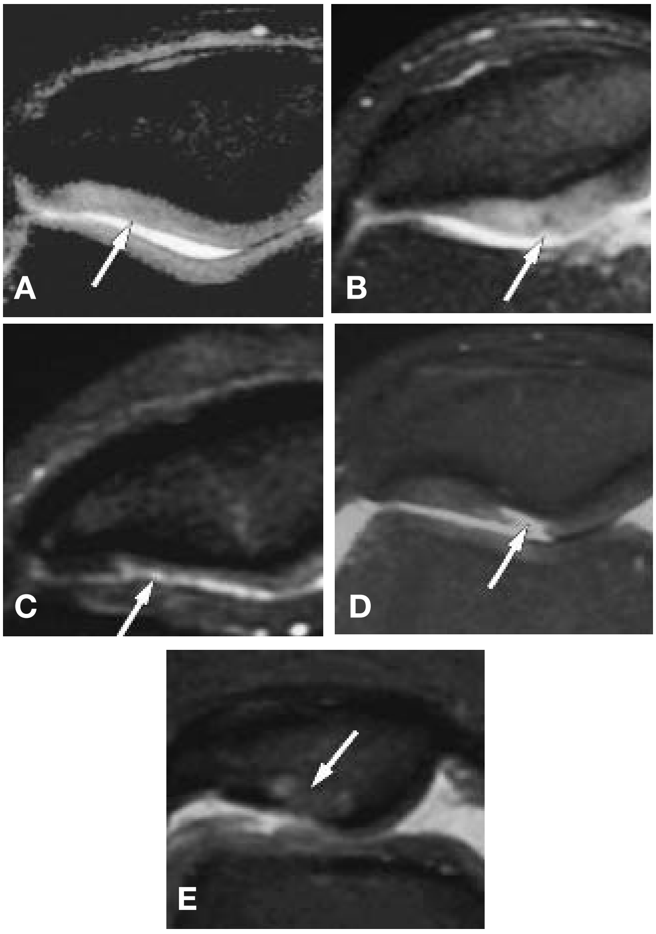

Figure 29. Grading system for articular cartilage defect. A, normal MR appearance of the patellar articular cartilage (arrow). B, grade 1 chondromalacia: surface irregularity (arrow) is less than 50% loss of articular cartilage. C, grade 2 chondromalacia: articular cartilage defect (arrow) is more than 50% of thickness but not full thickness. D, grade 3 chondromalacia: full-thickness articular cartilage defect (arrow) with normal underlying marrow signal. E, grade 4 chondromalacia: full-thickness articular cartilage defect with underlying bone marrow signal change (arrow).

condyle is associated with lateral patellar dislocation and disruption of the medial patellofemoral ligament (MPFL), as well as osteochondral injury of the patella or femur (Figure 27B).

Cartilage Abnormalities

Cartilage appears intermediate in signal intensity on T2-weighted or proton density images with fat saturation. It is clearly distinguishable from the dark signal of the adjacent osseous cortex and the bright signal of joint fluid (Figure 28). Cartilage defects of the tibia or femur are best seen on the sagittal and coronal images, whereas patellar abnormalities are best demonstrated on the axial images. Several cartilage-specific sequences have been developed to aid in the evaluation of articular cartilage of the knee, and although the accuracy for demonstrating lesions of the articular cartilage varies greatly depending on the equipment and pulse sequences used, studies have shown that using cartilage-specific imaging techniques can result in a sensitivity of 93% and a specificity of 94% for demonstrating arthroscopically visible lesions.[6]

Several cartilage-specific sequences have been developed; however, T2-weighted fast spin echo and proton density with fat saturation are the most common sequences used to evaluate cartilage. These sequences provide adequate signal-to-noise and adequate contrast to differentiate cartilage from the adjacent cortex of bone and joint fluid. T1-weighted images are poor for evaluating cartilage.[6,21] Abnormalities of cartilage are described using a 4-point grading system (Figures 29 A-E):

- Grade 1 (low-grade chondromalacia): irregularity of the articular cartilage with swelling and abnormal signal or mild thinning that is less than 50% of the articular cartilage thickness (Figure 29B).
- Grade 2 (intermediate-grade chondromalacia): thinning of the articular cartilage of more than 50% but not all the way to the underlying osseous cortex (Figure 29C).
- Grade 3 (high-grade chondromalacia): full-thickness cartilage loss but no underlying marrow signal change (Figure 29D).
- Grade 4 (high-grade chondromalacia): full-thickness cartilage loss with underlying marrow signal abnormalities (Figure 29E).

EXTENSOR MECHANISM

Normal Anatomy

The extensor mechanism is composed of the quadriceps tendon, the patella, and the patellar tendon. The integrity of these structures is best evaluated on T2-weighted sagittal MR images. The quadriceps tendon is a multilaminar structure made up of 4 separate tendons (rectus femoris, vastus medialis, intermediate, and lateralis) that merge to insert on the superior pole of the patella. The MR appearance is that of a striated structure, with fibro-fatty tissue commonly seen between the separate tendon slips. The patellar tendon, on the other hand, is a solid tendon and on MRI typically demonstrates homogeneous low signal intensity, with no internal striations.

The patella is stabilized by the medial and lateral soft tissue restraints. Medially, the MPFL is the primary stabilizer. The MPFL extends from the superior medial aspect of the patella to the adductor tubercle of the medial femoral condyle. This structure is clearly seen on axial images, and in cases of transient dislocation of the patella, the continuity of this ligament should be evaluated (Figures 30 A and B). Disruption of the MPFL most commonly occurs adjacent to the femoral attachment site at the level of the adductor tubercle on the medial femoral condyle. Look for complete disruption of the MPFL fibers or avulsion at the femoral attachment site.

Signs of Injury

Quadriceps Tendon

In chronic overuse injury or tendinopathy of the quadriceps tendon, MRI demonstrates thickening and increased T2 signal within the tendon. A complete tear of the quadriceps tendon will appear as complete discontinuity of the tendon with retraction of the proximal fibers (Figure 31A).[32]

Patellar Tendon

Chronic patellar tendinitis, or "jumper's knee," typically demonstrates abnormal signal located within the medial aspect of the tendon, near its patellar attachment (Figure 31B). An acute injury may result in a partial- or full-thickness tear of the patellar tendon, which will be seen on T2-weighted sagittal MR images as fluid signal within the expected location of the patellar tendon or as complete disruption and retraction of its fibers.[16]

Chondromalacia Patella and Lunge Lesion of the Trochlear Groove

The cartilage of the patella and trochlear groove is best evaluated in the axial and sagittal planes on T2-weighted or proton density images with fat saturation. The cartilage abnormalities are graded using the same grading system as described previously under the articular cartilage section (Figures 29 A-E). Isolated osteochondral injuries of the trochlear groove are referred to as "lunge" lesions and typically result from an injury that occurs during a lunging action. The cartilage of the trochlear groove is injured secondary to a shearing action of the patella impacting the trochlear groove.

Transient Lateral Dislocation of the Patella

The typical MR appearance reveals bone contusion involving the inferomedial patella and the anterolateral aspect of the lateral femoral condyle (Figure 27B).[13] Look for disruption of the MPFL, which most commonly occurs near

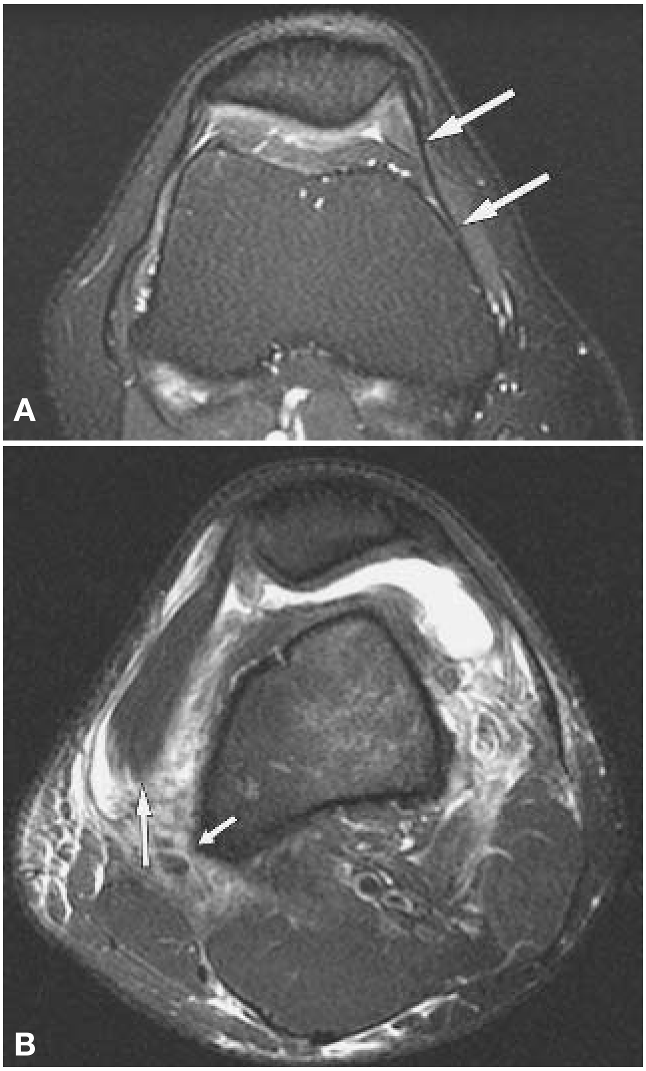

Figure 30. Medial patellofemoral ligament (MPFL). A, T2-weighted axial image of the right knee demonstrates the normal MR appearance of the MPFL (arrows) as a thin bandlike structure that extends from the superior pole of the patella to the adductor tubercle of the medial femoral condyle. It is located just deep to the vastus medialis obliquus (VMO) muscle. B, T2-weighted axial image of the left knee demonstrates disruption of the MPFL. There is stripping of the VMO (long arrow) off of the adductor tubercle (short arrow) with extensive edema deep to the VMO at the normal attachment site.

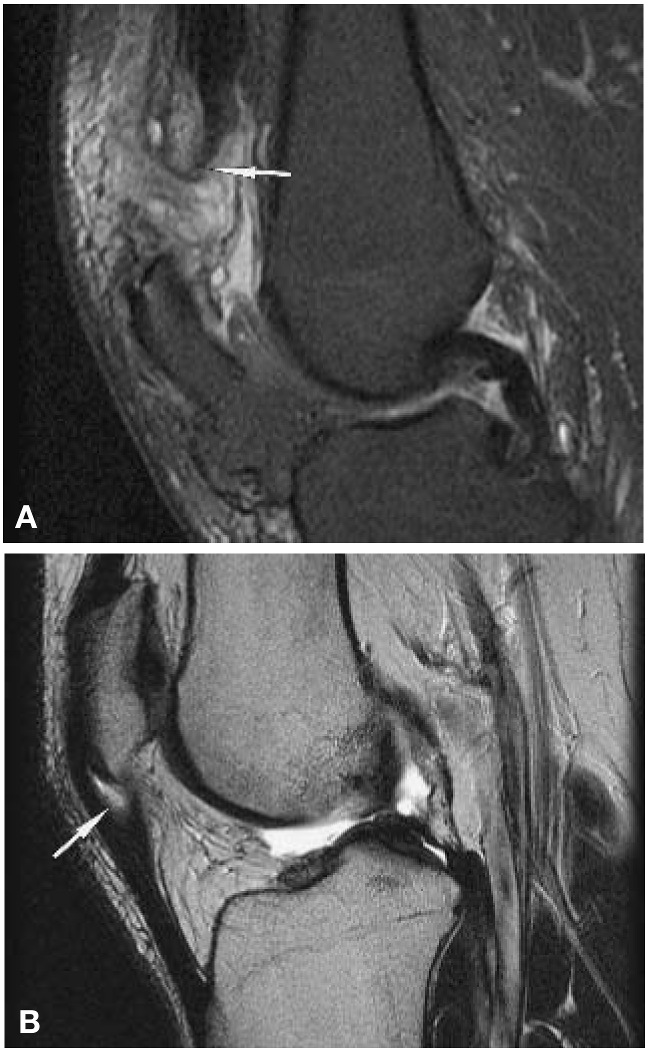

Figure 31. Quadriceps tendon tear/patellar tendinitis. A, T2-weighted sagittal image demonstrates fluid signal (arrow) completely traversing the quadriceps tendon, consistent with a complete tear. B, T2-weighted sagittal image demonstrates an area of high signal (arrow) and thickening of the proximal fibers of the patellar tendon, consistent with tendinitis.

the femoral attachment. The disruption of the MPFL is seen as complete discontinuity of the fibers or fluid between the proximal fibers of the MPFL and the adductor tubercle (Figure 30B). Also, the status of the articular cartilage of the inferomedial patella and the anterolateral femoral condyle should be evaluated.[27]

Miscellaneous

In this final section of the search pattern, all structures not evaluated in the earlier sections should be addressed. This may include joint effusions—graded as small, moderate, or large. Baker cysts, recesses that arise from the knee joint between the medial head of the gastrocnemius and the semimembranosus tendon, are also graded as small, moderate, or large. Miscellaneous entities not previously evaluated can also be described in this section. One such entity is the iliotibial band syndrome, which is a friction syndrome that occurs in long-distance runners when the iliotibial band (Figure 13A) rubs against the lateral femoral condyle, resulting in anterolateral knee pain. On MRI, this entity appears as edema within the soft tissues deep to the iliotibial band (Figure 14D), with occasional reactive marrow edema in the underlying lateral femoral condyle. This is best depicted on T2-weighted coronal images.[7] Several bursae are located in close proximity to

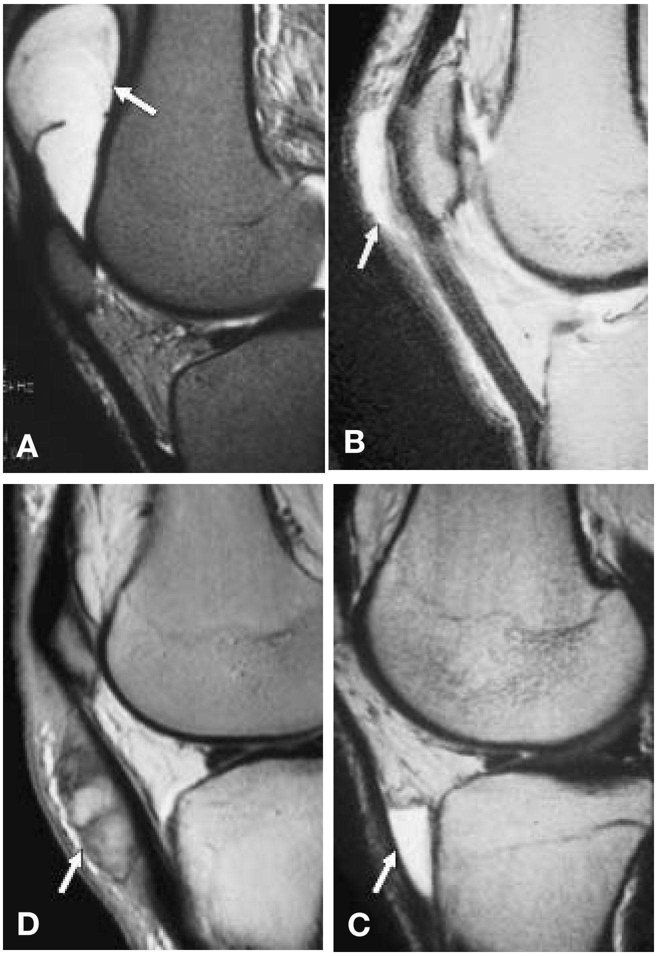

Figure 32. Extensor mechanism bursa. A, a large, isolated fluid collection (arrow) is located in the suprapatellar pouch (bursa). This usually occurs as a result of a thickened plica that leads to obstruction of the suprapatellar pouch, resulting in mass effect from a focal fluid collection. The condition can be treated by surgical resection of the obstructing plica. B, a fluid collection (arrow) is present in the prepatellar bursa, "housemaid's" knee. C, a fluid collection (arrow) is present within the deep infrapatellar bursa. This bursa, like the suprapatellar bursa, usually communicates with the joint space; however, if it becomes inflamed, it may obstruct and fill with fluid. D, a fluid collection (arrow) is present in the superficial infrapatellar bursa, consistent with bursitis.

the extensor mechanism and may become inflamed or fluid filled (Figures 32 A-D); these include the suprapatellar bursa, prepatellar bursa (housemaid's knee), and the deep and superficial infrapatellar bursa. Other bursae include the tibial collateral bursa, pes anserine bursa, tibial collateral semimembranosus bursa, and the lateral collateral biceps femoris bursa.[19]

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