INTRODUCTION

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Several technical advances in knee surgery have occurred in the areas of anterior cruciate ligament (ACL) reconstruction, meniscal repair and cartilage repair.

The number of surgical procedures performed and the number of patients that are now candidates for knee surgery are increasing.

MR examinations performed on patients with either persistent or recurrent knee pain in the postoperative setting have also increased and now comprise as many as 3 to 5% of all knee MR examinations in some practices.

Persistent or recurrent pain in the postoperative knee is a fairly common problem and MR imaging plays a definite role in the evaluation of these patients.[(1)]

Thus magnetic resonance (MR) imaging of the knee after surgical repair of internal knee derangements due to affection of the articular cartilage, the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the medial and lateral menisci is becoming more common.[(1)]

Relevant anatomy and sectional appearance

Anterior cruciate ligament

The ACL extends from the posteromedial aspect of the lateral femoral condyle to the anteromedial tibial plateau, just anterior to the intercondylar eminence.(2) The femoral attachment is not at the intercondylar notch, which is a common misconception.(2,3) On axial images it can be seen reliably on the first image in which the femoral articular cartilage is seen. The ligament is intra-articular but extra-synovial.(3) The ACL is significantly smaller in women, with respect to measurements of volume, mass, area, and length. (4, 5)

The ACL can be divided into anteromedial bundles (AMB) and posterolateral bundles (PLB) based on function, although there is no histologic separation.(3, 6) The bundles are named by their relative attachment sites on the tibia. The AMB restrains anterior tibial translation relative to the femur, whereas the PLB restrains rotation in near full extension.(7) The AMB rotates laterally around the PLB during knee flexion.(3) Distal fibers of the ACL may extend to the anterior and posterior horns of the lateral meniscus.(2,3)

An anatomic variant, consisting of a deltoid-shaped tibial attachment extending the length of the transverse meniscal ligament in the coronal plane, can predispose to impingement and synovitis.(8)

On MR imaging, the ACL is seen as an obliquely oriented band of low T1- and T2-weighted signal lying within the lateral aspect of the intercondylar notch (Fig. 1). On sagittal images with the knee extended, the ACL bundles are relatively parallel. The PLB is taut, whereas the AMB is slack.(2,7)

Imaging the knee with a mild degree of flexion, specifically 30 degrees, has been shown to decrease volume averaging in the region of the intercondylar notch, and thus better delineate the ACL.(9) The straight anterior border of the ACL should nearly parallel the Blumensaat line (roof of the intercondylar notch) (Fig. 2).(10,11)

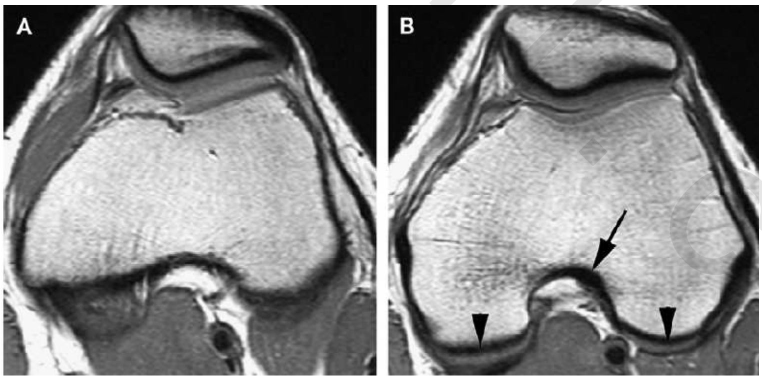

Figure 1: Normal femoral attachment of the ACL on proton density MR imaging.

(A) Axial section above common level of ACL origin and femoral articular cartilage.
(B) Axial level of ACL attachment (arrow) and femoral articular cartilage (arrowheads).(12)

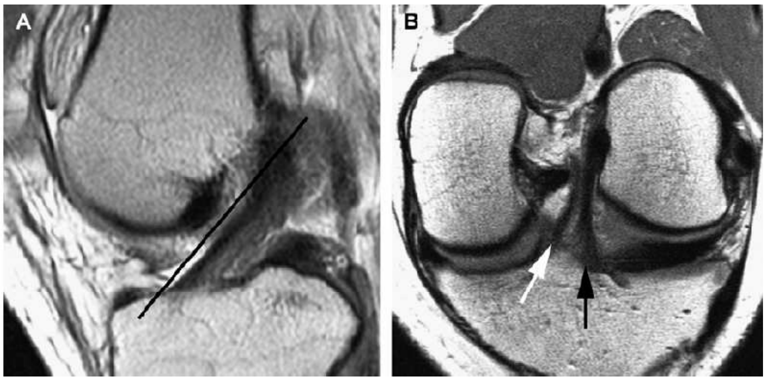

Figure 2: Normal ACL bundle anatomy on oblique coronal plane.
(A) Prescription plane (line) determined on sagittal T2-weighted image.
(B) Resultant oblique coronal plane demonstrating ACL AMB (white arrow) and ACL. PLB (black arrow).[12]

Posterior cruciate ligament

The PCL is larger and stronger than the ACL and functions to restrain posterior tibial translation relative to the femur. The femoral attachment is along the medial side and medial roof of the intercondylar notch. The tibial attachment is along the midline dorsal aspect of the tibial plateau, between the meniscal roots. The PCL tibial attachment also extends over the dorsal rim of the posterior tibial shelf.[13]

The PCL can be divided into two functional bundles, the anterolateral bundle (ALB) and the posteromedial bundle (PMB). The bundles are named based on the location of their femoral attachments. The two bundles maintain their anterior and posterior locations during motion of the knee and do not rotate around each other, as is seen with the bundles of the ACL. The ALB is larger and stronger, but has a codominant role with the PMB in stabilizing the knee.[14]

Additional posterior oblique fibers of the PCL have been described and can be confused with the posterior meniscofemoral ligament.[13]

The meniscofemoral ligaments extend from the posterior horn of the lateral meniscus to the medial femoral condyle. The meniscofemoral ligament lying posterior to the PCL is also known as the ligament of Wrisberg. The meniscofemoral ligament lying anterior to the PCL is also known as the ligament of Humphrey and may mimic an intact PCL in the presence of a PCL tear.[12]

On MR imaging with the knee in an extended position, the normal PCL is seen as a broad band of low T1- and T2-weighted signal, near the midline of the knee, extending from the femoral intercondylar notch to the posterior tibial plateau. On sagittal images with the knee extended, the PCL has a gently curved configuration (Fig. 3).[13]

Although the PCL is slack in the fully extended position, the PMB is relatively taut, compared with the ALB. The PCL shares function with the posterolateral corner structures in providing posterolateral rotatory stability. In flexion it becomes more taut and functional as the posterolateral corner structures become progressively lax (Fig. 3).[13]

A normal joint recess is located just posterior to the PCL, termed the PCL recess. This joint recess communicates with the medial femorotibial compartment and potentially can become isolated from the rest of the joint. An additional small joint recess lies between the ACL and PCL, termed the intercruciate recess. The intercruciate recess may communicate with either the medial or lateral femorotibial compartment.[15]

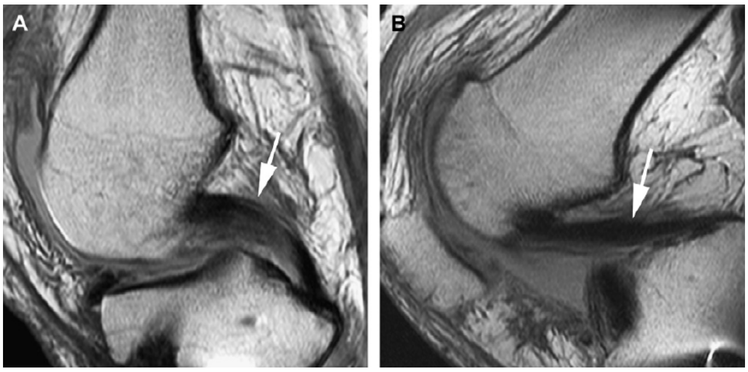

Figure 3: Normal PCL on sagittal proton density MR imaging in extension and flexion.

(A) Extension. PCL (arrow) is bowed normally, reflecting its laxity as the posterolateral corner is taut.
(B) Flexion (arrow). PCL is taut and provides most posterolateral rotatory stability when posterolateral corner structures are lax.[12]

Meniscal anatomy

The menisci are wedge-shaped, semilunar (C shaped), fibrocartilage structures composed of thick collagen fibers primarily arranged circumferentially, with radial fibers extending from the capsule, between the circumferential fibers.[16]

The superior surface of the meniscus is concave and the inferior surface is flat, allowing for maximal congruency between the femur and tibia. With weight bearing, the curved femoral condylar surfaces radially displace the menisci, creating circumferential hoop stresses.[16]

The circumferential arrangement of the type I collagen fibers provides the meniscus with tensile strength.[16] The menisci transmit more than 50% of body weight in extension, and even more in flexion.[17] These properties allow the meniscus to perform many functions, including the distribution of stresses over the articular cartilage, the absorption of shocks during axial loading, the stabilization of the joint in both flexion and extension, and joint lubrication; they also make a minor contribution toward secondary stabilization of the knee after cruciate ligament injuries.[16,18]

The menisci cover 50% of the medial and 70% of the lateral surface of the tibial plateau. [18] Typically, the medial meniscus is larger, has a wider posterior horn, and is more ‘‘open’’ toward the intercondylar notch, with the lateral meniscus typically smaller and more ‘‘closed’’ toward the notch. In adults, the vascularized area, commonly known as the ‘‘red zone,’’ involves the outer 10% to 30% of the meniscus (Fig. 4).[18,19]

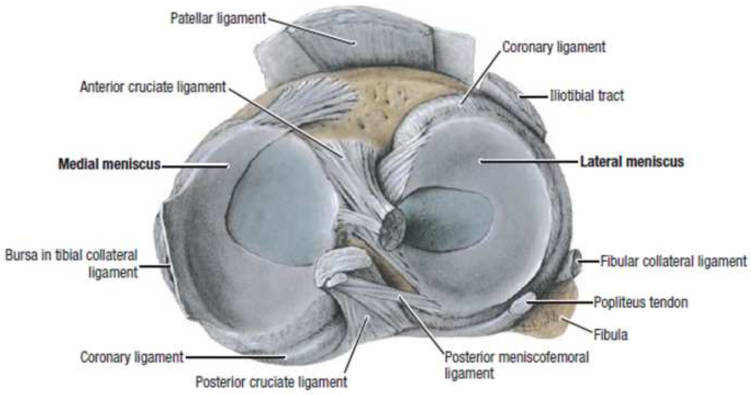

Figure 4: Superior view of the menisci.[20]

Each meniscus is divided into an anterior horn, a body, and a posterior horn. Usually, the anterior horn of the medial meniscus is attached to the tibial plateau anterior to the anterior cruciate ligament (ACL).[18]

The anterior horn of the lateral meniscus has fibers of the ACL that extend into it at the anterior root attachment where it attaches to the tibial plateau.[21]

The transverse or anterior intermeniscal ligament, which is noted in 44% to 58% of patients on MR, has variable attachments; however, 58% of the time it runs between the anterior horn of the medial meniscus and the anterior margin of the lateral meniscus, connecting the two anterior horns.[21]

The posterior horn of the lateral meniscus attaches to the posterior tibia, and usually has attachments to the medial femoral condyle and the popliteus by way of the meniscofemoral ligaments and the popliteomeniscal fascicles, respectively. The posterior horn of the medial meniscus attaches to the tibial plateau immediately anterior to the posterior cruciate ligament (PCL).[18]

The meniscofemoral ligaments extend from the posterior horn lateral meniscus usually to the lateral aspect of the posterior medial femoral condyle, but occasionally to the PCL. The incidence of at least one meniscofemoral ligament identified on MR ranges from 66% to 93%, with both identified in anatomic studies more than 30% of the time.[22, 23]

Typically, when both are present, one is notably thicker. They have properties similar to the posterior bundle of the PCL and may supplement the PCL, providing secondary restraint. The ligament of Humphrey is anterior and the ligament of Wrisberg is posterior to the PCL (Fig. 5).

The meniscofemoral ligaments oppose the posterior movement of the posterior horn of the lateral meniscus and ‘‘pull’’ the posterior horn of the lateral meniscus anteriorly and medially.[22]

The popliteomeniscal fascicles are synovial attachments of the posterior horn of the lateral meniscus that extend around the popliteus bursa. The superior fascicle arises from the medial fibers of the popliteus tendon aponeurosis, and the inferior fascicle extends from the meniscus to the tibial margin (Fig. 6).

At least one fascicle is visualized in 97% of patients with an intact lateral meniscus, best seen on T2-weighted images.[24] The fascicles control the motion of the lateral meniscus in flexion and extension.

Disruption of the fascicles allows increased meniscal movement,[22] meniscal subluxation, and even locking of the knee.[24] Along with the popliteus muscle, these structures oppose the forces of the meniscofemoral ligaments.[22]

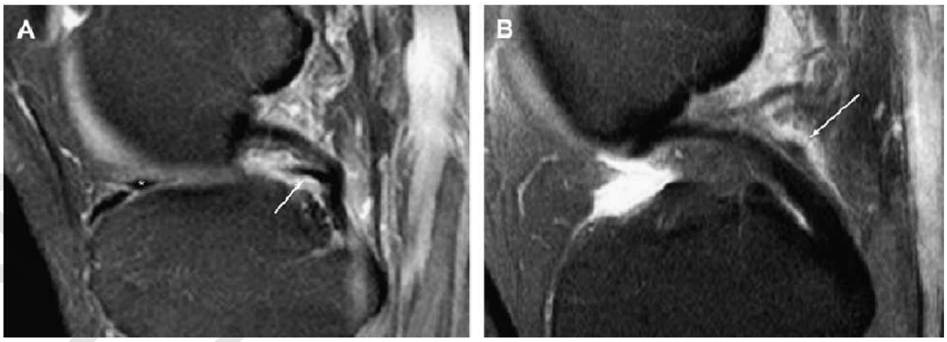

Figure 5: **(A)** Sagittal gradient echo image of the ligament of Humphrey located anterior to the PCL (arrow). Also noted is the anterior or transverse intermeniscal ligament (asterisk). **(B)** Sagittal fast spin-echo (FSE) fat-saturated proton density–weighted image of the ligament of Wrisberg, located posterior to the PCL (arrow).[25]

Figure 6: Sagittal proton density–weighted fat-saturated image of the superior (thin arrow) and inferior (thick arrow) popliteomeniscal fascicles attaching to the posterior horn of the lateral meniscus, with the popliteus tendon (asterisk) in between [25]

Meniscal variants

Many meniscal variants have been reported. Some of the variants described more commonly include the discoid meniscus, meniscal ossicles, and the meniscal flounce.[25]

The discoid lateral meniscus has a reported incidence of 0.4% to 16.6% and is more common in the Japanese and Korean populations.[26] Joint line tenderness is noted in 73%, ‘‘snapping’’ in 49%, and locking of the knee in 21% of patients.[27] The three types of discoid lateral meniscus are complete, incomplete, and the Wrisberg variant. Some investigators include a ring-shaped meniscus as a fourth type.[28]

The complete and incomplete types have a firm, normal posterior tibial attachment and are stable. Symptomatic patients who have these types of discoid menisci usually are treated with a partial meniscectomy.[29, 30]

In contrast, the Wrisberg variant has no posterior coronary or capsular attachments and increased T2 signal is present between the meniscus and the capsule, simulating a peripheral tear or a fascicular injury. The Wrisberg variant has the most notable symptoms, with a ‘‘snapping’’ sensation occurring when the posterior horn moves across the femoral condyle during flexion and extension.[30]

A discoid medial meniscus is much less common, with the incidence reported to be 0.12% to 0.6%.[17, 31, 32]

On MR, the diagnosis of a discoid meniscus is suggested by identifying either meniscal tissue on three continuous sagittal 5-mm-thick slices, or a meniscal body on coronal images greater than 15 mm wide or extending into the intercondylar notch (Fig 7).[30, 31]

The discoid meniscus has an increased incidence of tears and degeneration, likely caused by its abnormal shape, resulting in increased stress on the meniscus.[32-34] Intrasubstance ‘‘grade 2’’ signal, or abnormal signal not extending to an articular surface, is noted in 24% of discoid menisci and is more common in complete discoid menisci.[34]

Typically, this abnormal signal is not considered clinically significant however, in the population with discoid menisci, some investigators report that this intrasubstance signal may be significant clinically.[33, 34]

Meniscal ossicles are reported in 0.15% of patients and are thought to be either developmental or posttraumatic. These small, ossific foci are found typically in the posterior horn of the medial meniscus and are associated with meniscal tears. They can be asymptomatic, or associated with pain and a sensation of locking, clinically simulating a torn meniscus with a flap component. The ossicle follows the signal of bone marrow on MR.[35]

Meniscal flounce is a wavy appearance along the free edge of the meniscus. Previously, meniscal flounce was thought to be identified only at arthroscopy, in the presence of joint fluid with the knee flexed, the tibia rotated externally, and a valgus force applied, exposing the posterior-medial compartment of the knee, or in the setting of an ACL or medial collateral ligament (MCL) tear. However, a flounce can be seen without a ligament injury.[36,37]

Recently, the meniscal flounce has been identified with MR imaging when the knee is in 10 degrees of flexion. The flounce completely resolves when the knee is extended maximally, and resolves nearly 50% of the time when the knee is flexed maximally.[38]

The flounce can appear truncated on coronal images and can simulate a tear or degeneration. The incidence at MR is reported to be from 0.2% to 6%. A flounce-like appearance can be seen with meniscal tears (Fig. 8).[36,37]

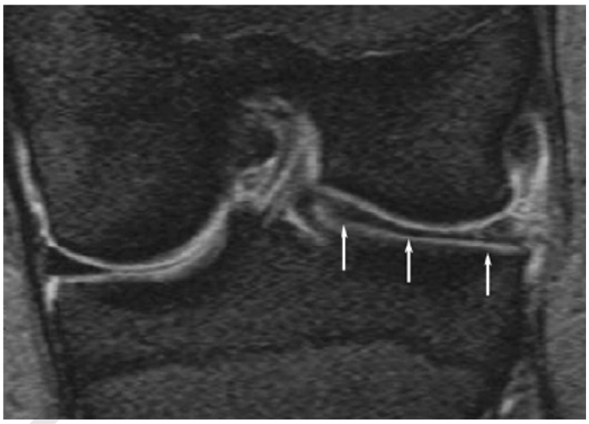

Figure 7: GRE coronal image demonstrating a discoid lateral meniscus (arrows).[25]

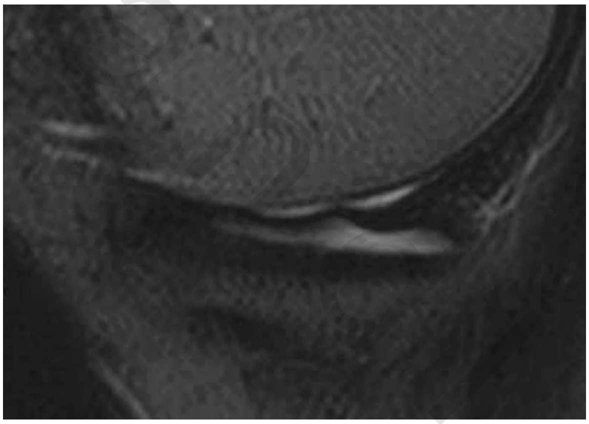

Figure 8: T2-weighted fat-saturated sagittal image demonstrating a flounce like appearance to the posterior horn and body of the medial meniscus, in the setting of a meniscal tear.[25]

Articular cartilage

Hyaline cartilage is an important intra-articular tissue that may be involved in traumatic injury to and degenerative change in the knee joint. Damaged cartilage rarely heals spontaneously, and its subsequent degeneration in association with degeneration of other articular tissues may lead to knee osteoarthritis, which is both a cartilaginous and a whole-organ disease.[39]

In recent decades, magnetic resonance (MR) imaging has become the most important modality for assessment of pathologic changes in knee cartilage, in both clinical and research environments.

One of the major advantages of MR imaging is that it allows the manipulation of contrast to highlight different tissue types. The new surgical and pharmacologic options available to treat damaged cartilage, and the need to monitor the effects of treatment, have led to development of various MR imaging techniques that allow morphologic assessment of cartilage, quantification of its volume, and evaluation of its biochemical composition.[40-45]

Morphologic assessment of the Articular Cartilage

MR imaging techniques for morphologic assessment of cartilage in the knee provide accurate information about processes such as fissuring and focal or diffuse partial- or full-thickness cartilage loss.

Morphologic MR imaging assessment of cartilage repair provides accurate postoperative information about specific parameters that are selected according to the surgical technique used.[43, 44]

Each technique has its strengths and weaknesses for various clinical applications, and the physician or researcher must consider these carefully.

Fat Suppression Techniques

A fat suppression technique may be used to increase the contrast between lipid surfaces and non lipid surfaces, add dynamic range, and reduce chemical shift artifacts. In cartilage imaging, fat suppression techniques provide increased contrast at the subchondral bone–cartilage interface.

The most commonly used technique is fat saturation, which involves the excitation and dephasing of the spinning protons in fat by a lipid-specific radiofrequency pulse applied before each repetition of a 2D or 3D SE or GRE imaging sequence.

One disadvantage of using this fat saturation technique in combination with the 3D GRE sequences is that it lengthens the acquisition time.[46]

Furthermore, this chemically selective fat saturation technique is vulnerable to magnetic field inhomogeneities produced by magnetic susceptibility differences due to local factors (eg, the presence of metallic hardware), a common problem during MR imaging of the knee.

Iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL) can provide uniform fat suppression in the challenging magnetic field environments of knee imaging while maintaining a high SNR (Fig. 9). This three-point water-fat separation technique relies on the use of asymmetric echoes and least squares fitting to maximize SNR performance, and it can be used in conjunction with either an SE or a GRE technique.[47]

Another alternative option is a spectral excitation technique in which only water spins in a surface are excited.[48]

Short time inversion recovery (or STIR) imaging is another option for assessing areas that may be affected by magnetic field inhomogeneity. This technique provides fat suppression, allowing accurate depiction of cartilaginous defects in the knee joint (Fig. 10).[49]

Water excitation imaging is based on the selective excitation of non–fat-bound protons. A short TR of approximately 18 msec and a small flip angle (15°–40°) are usually used to depict cartilage with high signal intensity and high contrast to surrounding tissue.

The use of water excitation provides the major advantages of reducing acquisition time and ameliorating chemical shift artifacts.[50]

Water excitation also may be applied for quantitative assessments of cartilage thickness and volume.[51]

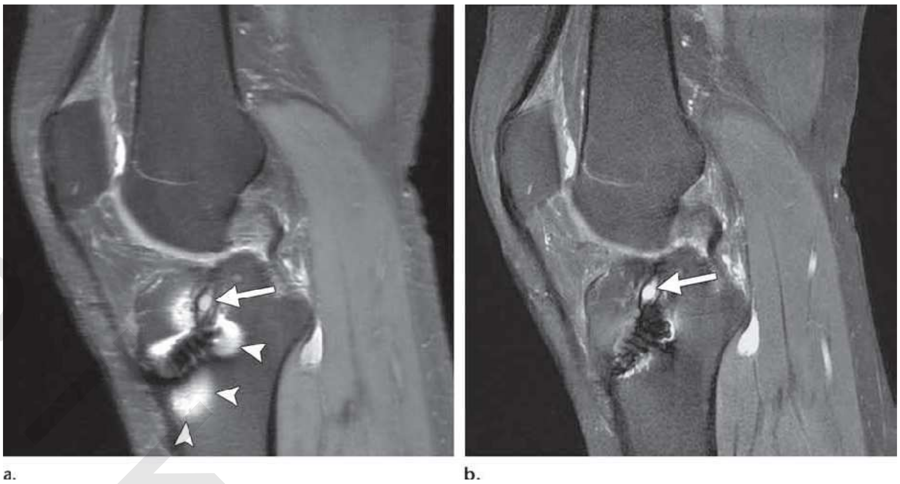

Figure 9: **(a)** Sagittal intermediate-weighted fat-saturated fast SE image (TR msec/echo time [TE] msec = 4000/35) shows regions of high signal intensity due to poor fat saturation (arrowheads) adjacent to a tibial interference screw (arrow).

(b) Sagittal intermediate-weighted IDEAL fast SE water image (TR/TE = 4000/35) depicts a cyst adjacent to the interference screw (arrow). The signals from fat and water are better differentiated with this technique.[52]

Figure 10: Axial short inversion time inversion recovery image obtained in the knee accurately depicts a focal full-thickness chondral defect (arrows) at the trochlear groove.[52]

Two-dimensional SE and Fast SE Imaging

The MR imaging sequences most commonly used in the assessment of joint cartilage are 2D or multisection T1-weighted, proton density–weighted and T2-weighted imaging sequences with or without fat suppression.(53)

T1-weighted images show intrasubstance anatomic detail of hyaline cartilage but do not provide good contrast between joint effusion and the cartilage surface, a shortcoming that limits their usefulness in the assessment of focal cartilaginous defects (Fig. 11).(53)

Furthermore, T1 weighting has poor capability for depicting other internal structures in the knee, such as ligaments, and may lead to overestimation of meniscal abnormalities.(54)

T2-weighted imaging provides good contrast between the cartilage surface and joint effusion, which is useful for detecting focal areas of delamination or other defects (Fig. 12). However, it does so at the expense of the internal cartilage signal, which is weakened because some components of cartilage have short T2.(54)

Although proton density– weighted imaging is capable of depicting surface cartilaginous defects as well as abnormalities of internal cartilage composition, several institutions prefer to use intermediate-weighted sequences that combine the contrast advantage of proton density weighting with that of T2 weighting by using a TE of 33–60 msec.(52)

These sequences provide higher overall signal intensity in cartilage than standard T2-weighted sequences do (Fig. 13), allowing better differentiation between cartilage and subchondral bone. In addition, they are less susceptible to the magic angle effects seen in proton density–weighted imaging with a shorter TE.(52)

Figure 11: Sagittal 2D fast SE images obtained with various techniques in the same knee. (a) T1-weighted image shows poor contrast between the cartilage surface and synovial fluid, a disadvantage that prevents accurate assessment of a focal cartilaginous defect (arrowheads). (b, c) T2- weighted (b) and proton density–weighted (c) images provide better contrast between the cartilage surface and synovial fluid, allowing identification of a full-thickness cartilaginous defect (arrowheads) in the medial femoral condyle. A tear of the posterior horn of the medial meniscus also is visible in a–c.(52)

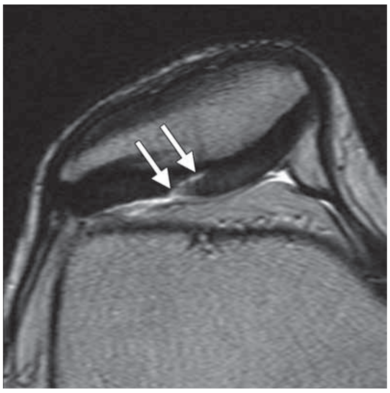

Figure 12: Axial 2D T2-weighted fast SE image provides excellent depiction of a focal region of deep cartilaginous delamination (arrows), with high contrast between the cartilage surfaces and synovial fluid.[52]

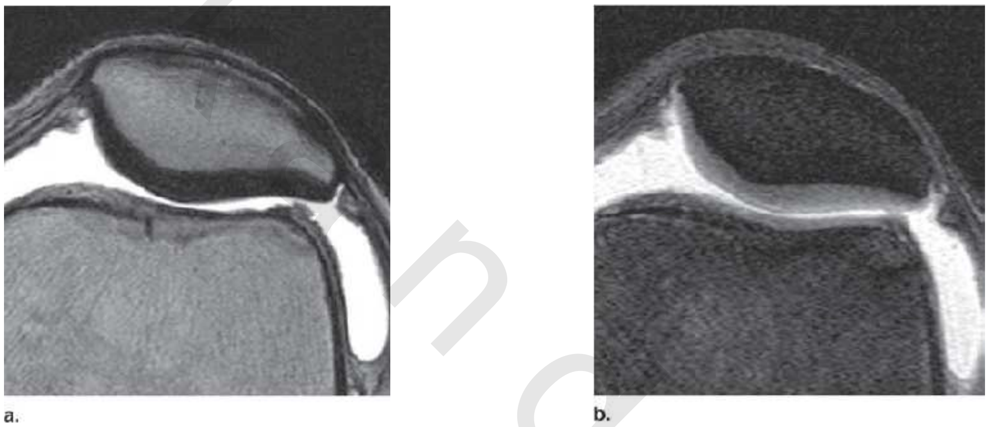

Figure 13: **(a)** Axial 2D T2-weighted non–fat suppressed fast SE image provides excellent contrast between cartilage surfaces and synovial fluid, but the cartilage is poorly depicted with diffuse low signal intensity, and there is no contrast between cartilage and cortical bone. **(b)** Axial 2D intermediate-weighted fat suppressed fast SE image shows excellent contrast among cartilage surfaces, synovial fluid, and subchondral bone, as well as variation of signal intensity within the cartilage.[52]

Three-dimensional Fast SE Imaging

Recently, 3D intermediate-weighted fast SE sequences have been applied to obtain images of the knee joint with high contrast resolution and isotropic spatial resolution.[52]

This technique, which relies on flip angle modulation to reduce blurring and parallel imaging to reduce acquisition time, has made high-contrast isotropic imaging possible in the clinical setting. Fast SE pulse sequences and other MR imaging techniques that provide isotropic spatial resolution allow high-quality multiplanar reformatting of image data for 3D evaluation of the anatomy (Fig. 14).[52]

Furthermore, unlike 3D GRE sequences, 3D FSE sequences provide good depiction of subchondral bone marrow abnormalities.

Figure 14: **(a)** Coronal 3D intermediate-weighted fast SE source image (TR/TE = 3000/35) obtained with isotropic spatial resolution (acquired section thickness of 0.6 mm, averaged to 2.4 mm; acquisition time, 5 min) shows no cartilage abnormalities. (b, c) Axial **(b)** and sagittal **(c)** images obtained with reformatting of the coronal source image dataset show a focal chondral defect (arrow) at the trochlear groove.[52]

SPGR Imaging (Spoiled gradient recalled echo)

Three-dimensional SPGR imaging is considered the standard technique for morphologic evaluations of knee cartilage because it offers higher sensitivity than 2D techniques and provides excellent depiction of cartilaginous defects.[46, 55]

In 3D SPGR imaging, the transverse steady state is spoiled by semirandom alterations in the phase of the radiofrequency pulse to obtain contrast similar to that of T1-weighted or proton density–weighted imaging. An SPGR sequence is available on most MR imaging systems and is useful whenever the evaluation of cartilage is required.[52]

SPGR imaging increases the signal intensity of cartilage in relation to that of adjacent tissues and joint contents such as fluid (Fig 15).[52]

Furthermore, this technique allows the acquisition of nearly isotropic voxels, providing high-resolution 3D image data that are ideal for avoiding partial volume artifacts and achieving accurate quantitative assessment of cartilage thickness and volume[52]

Lipid suppression is often achieved by using fat saturation, but it may also be obtained with water excitation.[52]

This technique has some disadvantages. First, small focal lesions may be obscured because of the lack of reliable contrast between cartilage and fluid that outlines surface defects.[52]

Second, the technique is unreliable for assessing knee structures other than articular cartilage: Magic angle effects may lead to false-positive findings in ligaments and menisci, and magnetic susceptibility effects may obscure bone marrow abnormalities.[52]

Third, long acquisition times may lead to motion artifacts and less accurate measurements, although these problems may be less severe with current MR imaging systems.[52]

Fourth, the technique is highly vulnerable to susceptibility artifacts. Furthermore, the gradient and radiofrequency spoiler pulse applied at the end of each sequence repetition to decrease artifacts and obtain near–T1-weighted cartilage-to-fluid contrast also results in lower overall signal intensity, compared with that obtained with steady-state imaging techniques.[52]

In a recent study, high-resolution images of knee joint cartilage were obtained with an increased SNR, better cartilage-to-fluid contrast, and shorter acquisition time with combined IDEAL and SPGR sequences than with a standard fat-saturated SPGR sequence alone.[56]

Fast low-angle shot (FLASH) imaging is an SPGR-type technique in which a random gradient pulse is used to produce a phase shift and spoil the steady state, with the same goal of achieving proton density–weighted or T1-weighted contrast resolution.[57]

With a demonstrated diagnostic performance commensurate with that at 2D SE and 3D GRE imaging in the detection of cartilage defects, FLASH imaging is an accepted technique for morphologic assessments of articular cartilage in the knee.[57]

Lipid suppression is usually achieved with an additional fat saturation or water excitation pulse. Normal cartilage has high signal intensity on FLASH images, a characteristic that makes surface lesions more visible but may impede the detection of internal cartilage defects such as fissures.[52]

The FLASH technique allows the acquisition of high-spatial-resolution images, but the long acquisition time may lead to motion artifacts. Furthermore, the technique is vulnerable to susceptibility artifacts, which may lead to underestimation of the extent of associated bone marrow changes—a potential disadvantage when evaluating the effectiveness of cartilage repair procedures (Fig. 16).[52]

Figure 15: Coronal 3D SPGR image shows intact high signal-intensity cartilaginous surfaces in the medial and lateral tibiofemoral compartments. Lipid suppression provides excellent contrast between cartilage and subchondral bone.[52]

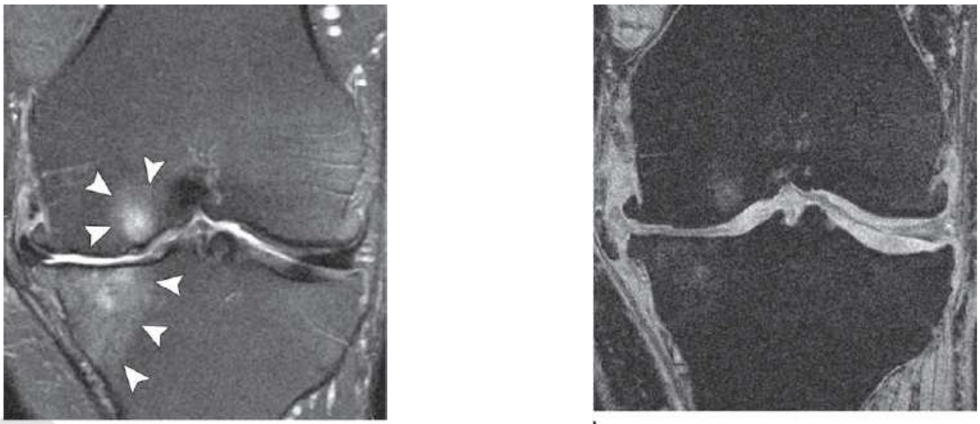

Figure 16: **(a)** Coronal T2-weighted fat-suppressed image shows large areas of complete loss of cartilage in the medial tibiofemoral compartment with associated edematous degenerative lesions in subchondral bone marrow (arrowheads). Large osteophytes and medial meniscal extrusion also are seen. **(b)** Coronal 3D FLASH image accurately depicts the areas of complete loss of cartilage in the medial compartment as seen in a, but the associated bone marrow lesions are barely visible.[52]

DEFT Imaging (Driven equilibrium Fourier transform)

DEFT imaging, which is based on the active return of magnetization to the z-axis after each excitation, increases contrast between fluid and cartilage by enhancing the synovial fluid signal while preserving the signal from cartilage.[58]

Because of the short TE in DEFT imaging, the fluid signal intensity is higher than that in SPGR imaging and the cartilage signal intensity is higher than that in T2-weighted fast SE imaging.[58]

Contrast between tissues is dependent on the ratio of T1 to T2 in each tissue, and cartilage-to-fluid contrast is higher with a short TR at DEFT imaging than at imaging with proton density–weighted fast SE, T2-weighted fast SE, or SPGR techniques (Fig. 17).[58]

Lipid suppression is often achieved with a fat saturation pulse. Diagnostic performance with DEFT imaging for the detection of cartilaginous lesions in the knee is comparable to that with standard 2D techniques and SPGR sequences.[59]

The disadvantages of DEFT imaging are its (a) vulnerability to motion artifacts due to long acquisition times; (b) often inadequate fat saturation; and (c) insensitivity to bone marrow changes such as edema, which can lead to underestimation of the extent of bone marrow lesions.[59]

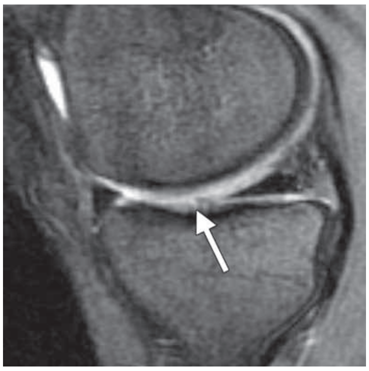

Figure 17: Sagittal 3D DEFT image demonstrates a cartilage fissure (arrow) at the medial tibial plateau. The defect is outlined by the high signal intensity of synovial fluid, an appearance that derives from the driven equilibrium acquisition technique.[52]

DESS Imaging (Dual-echo steady state)

In 3D dual-echo steady-state (DESS) imaging, two or more gradient echoes are acquired, with each group of two echoes separated by a refocusing pulse and with the data from both echoes combined to obtain higher T2* weighting for high signal intensity in cartilage and synovial fluid.

Depending on the parameters used to acquire 3D DESS images, contrast between the cartilage surface and synovial fluid may be too slight to clearly delineate small cartilaginous defects. However, an increase in the flip angle results in substantially increased contrast between cartilage and synovial fluid and better depiction of subtle cartilaginous lesions (Fig. 18).[60]

Lipid suppression may be achieved with a fat saturation or water excitation technique. Studies have demonstrated the usefulness of 3D DESS imaging for the morphologic assessment of knee cartilage.[61]

Because acquisition time for DESS imaging is shorter than that for 3D SPGR imaging, it is less vulnerable to image artifacts from patient motion and more likely to allow accurate assessments.

Other advantages of the technique include potentially higher SNR; higher cartilage-to-fluid contrast; and thinner sections with near-isotropic resolution, helping reduce partial volume effects.

Because cartilage demonstrates high signal intensity, internal changes in cartilaginous signal intensity may be difficult to detect with this technique.

However, the capability of this technique for assessing adjacent structures such as menisci and ligaments has not been well validated.[52]

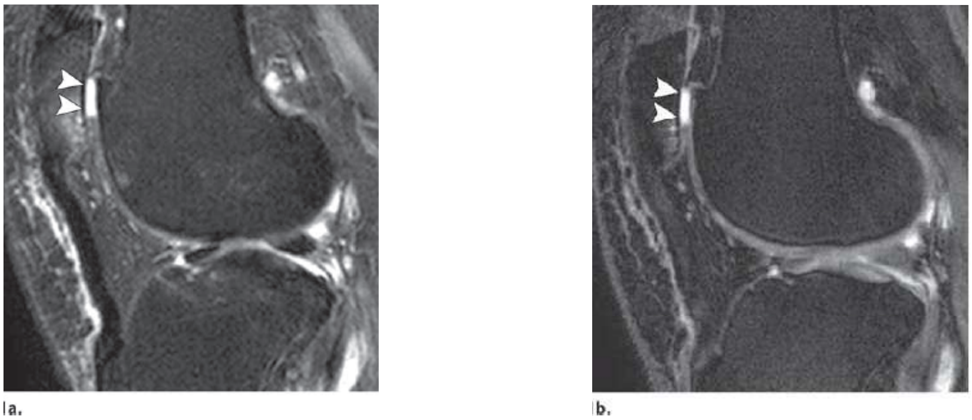

Figure 18: Sagittal T2-weighted fat-suppressed fast SE image (a) and water excitation DESS image obtained with a flip angle of 90° (b) both accurately depict a full-thickness cartilaginous defect (arrowheads) at the patella in another patient.[52]

bSSFP Imaging (Balanced steady state free precession)

In 3D bSSFP imaging, as in 3D DESS imaging, cartilage displays high signal intensity, but the parameters vary somewhat from those in DESS imaging.

Other names for 3D bSSFP imaging are true FISP (true fast imaging with steady-state precession), FIESTA (fast imaging employing steady-state acquisition), and balanced FFE (fast field echo) imaging.

Three-dimensional bSSFP imaging depicts fluid with increased signal intensity while preserving the signal intensity of cartilage, providing excellent synovial fluid–cartilage contrast.

Diagnostic performance with 3D bSSFP imaging is similar to that with standard 2D sequences and commonly used 3D GRE sequences for the morphologic assessment of knee cartilage (Fig. 19).[57,62] The technique also is useful for imaging other internal structures of the knee, such as ligaments and menisci,[63] a capability that makes it an attractive option for clinical practice.

A variant of bSSFP imaging called fluctuating equilibrium MR (or FEMR) imaging is useful for the morphologic assessment of knee cartilage,[64] producing 3D images within a short acquisition time.[65]

This technique also provides excellent cartilage-to-fluid contrast, depending on the ratio of T1 to T2 in these tissues, producing a bright fluid signal while maintaining high signal intensity of cartilage.

Fluctuating equilibrium MR imaging provides greater SNR efficiency in cartilage than standard techniques such as proton density–weighted fast SE, T2-weighted fast SE, and 3D SPGR imaging.[64]

However, like bSSFP imaging, fluctuating equilibrium MR imaging is vulnerable to off-resonance artifacts. Furthermore, its use in the assessment of other internal structures in the knee has not yet been validated.

Lipid suppression in bSSFP imaging can be achieved with several methods. When the TR is short and the magnetic field is homogeneous, a conventional fat saturation or water excitation pulse may be used.

Other methods for achieving lipid suppression or fat-water separation with bSSFP imaging include Dixon imaging, which allows excellent differentiation of fat from water; linear combinations of bSSFP; and intermittent fat suppression, in which transient fat saturation pulses are applied to suppress the lipid signal.(52)

IDEAL imaging may be applied in conjunction with bSSFP imaging with multiple acquisitions to separate fat and water, with higher SNR efficiency in fluid and higher fluid-cartilage CNR efficiency than are achievable with fat-saturated bSSFP imaging.(65)

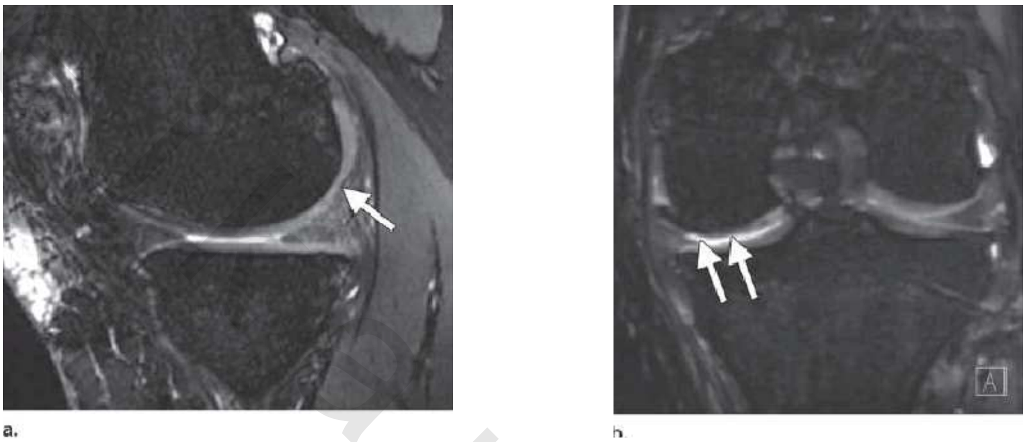

Figure 19: **(a)** Sagittal 3D water excitation bSSFP source image shows a focal partial-thickness cartilaginous defect (arrow) at the medial femoral condyle. **(b)** Coronal reformatted image shows the extent of the defect (arrows). A medial femoral osteophyte and medial meniscal extrusion also are depicted.(52)

VIPR Imaging (Vastly undersampled isotropic projection reconstruction)

VIPR-SSFP, a recently developed technique based on the combination of bSSFP imaging with 3D radial k-space acquisition, allows the acquisition of images with isotropic spatial resolution and T2/T1-weighted contrast.[66] The radial acquisition technique provides more efficient filling of k-space by collecting two radial lines per TR and omitting frequency dephasing and rephasing gradient pulses.

Linear combinations of bSSFP are used to separate the fat signal from the water signal.[52]

VIPR imaging provides isotropic 0.5- to 0.7-mm-thick 3D image sections, allowing reformatting in arbitrarily selected planes.

This technique results in a high SNR in cartilage and high contrast between cartilage and adjacent joint structures (Fig. 20), allowing an excellent diagnostic performance in the detection of cartilaginous, meniscal, and ligamentous lesions in the knee, as well as associated bone marrow changes.[66]

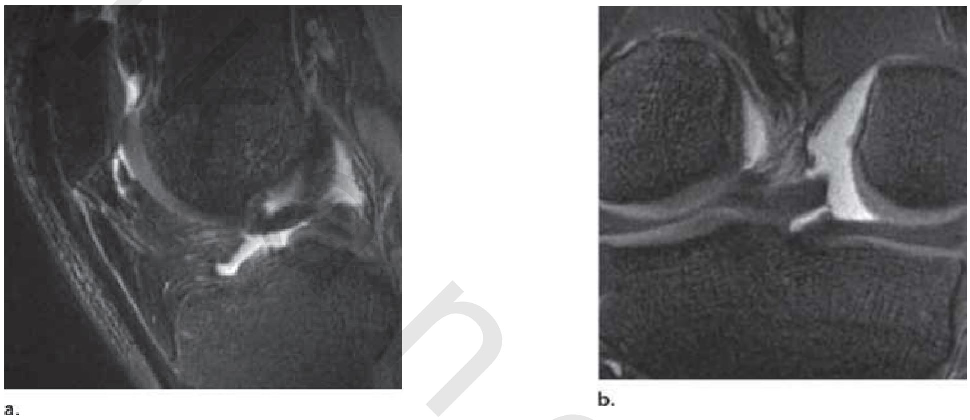

Figure 20: Sagittal source (a) and coronal reformatted (b) 3D VIPR-SSFP images exhibit a high cartilage SNR and high contrast among cartilage, synovial fluid, and other joint structures.[52]

Anterior cruciate ligament acute injury

Typical tears

The ACL should be examined in sagittal, coronal, and axial planes for abnormal increased T2- weighted signal or abnormal contour. An oblique coronal plane, prescribed along the line of the ACL in the sagittal plane, may be of help in low grade or chronic injuries, or to evaluate the reconstructed ACL.[11]

Signs of a tear include discontinuous fibers, non visible fibers, and abnormal slope of the ligament. The sagittal plane (Fig. 21) is most helpful for evaluation of the linear configuration of the ACL fibers. Axial (Fig. 22) and coronal images can confirm findings seen on sagittal images.[11]

An oblique sagittal imaging plane can be plotted through the intercondylar notch region and oriented along the course of the ACL. This additional sequence is plotted best using a coronal localizing sequence.[67]

Fluid-sensitive sequences, including T2- weighted and proton density sequences are the most sensitive for injury evaluation of the ACL and surrounding soft tissues.

T1- weighted and gradient echo sequences are useful to assess for additional injuries in the bones and cartilage.

Tears range from low grade, partial thickness to full thickness and are located most commonly in the mid- to proximal aspect of the ligament. ACL tears occur up to eight times more commonly in females than in males.[10,68,69]

A torn ACL fiber has increased T2-weighted signal and an abnormal contour. In some full-thickness tears, an amorphous mass replaces the discrete ACL fibers. Fluid can fill the gap between the fibers of a full-thickness tear (Fig. 23).

The location of the tear can be described as proximal (Fig. 24), midsubstance, distal, or involving the femoral or tibial attachment. Women are more likely to have tears involving the proximal ACL, likely because of the higher incidence of noncontact inciting mechanisms. [69-71]

If the ACL is torn partially, most commonly the AMB is involved. Avulsion of the ACL from the tibial attachment site is more common in young patients.[72]

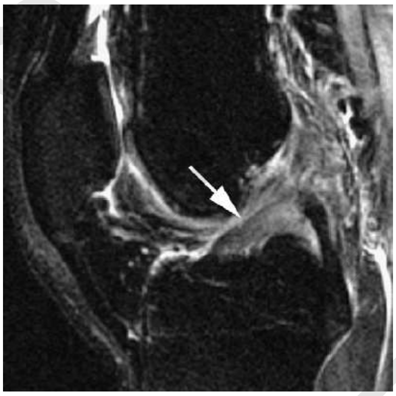

Figure 21: Partial-thickness tear of the ACL on sagittal fat-suppressed proton density MR imaging. The ACL (arrow) has diffusely increased signal. The normal parallel course of the fibers is disrupted. The ACL also has an abnormally horizontal orientation.[12]

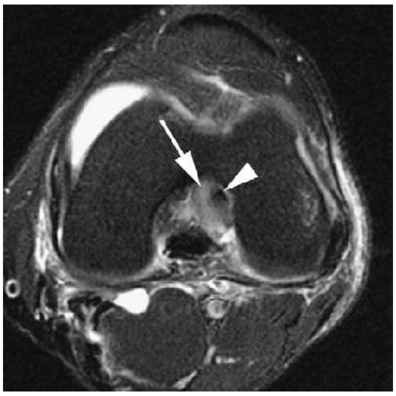

Figure 22: Partial-thickness ACL tear on corresponding axial T2-weighted MR imaging in same patient as in Fig. 19. Increased signal within the ACL AMB (arrow) with residual intact fibers indicates partial-thickness tearing. The adjacent PLB (arrowhead) has normal low signal intensity.(12)

Figure 23: Full-thickness tear of the ACL on sagittal fat suppressed T2-weighted MR imaging. Fluid fills the tear (arrow) in the mid portion of the ligament.(12)

Figure 24: Near full-thickness tear of the proximal ACL on fat-suppressed proton density MR imaging. The proximal ACL (arrow) is seen as a stump of intermediate signal. A few of the anterior superior fibers may remain attached.(12)

Associated injuries and findings

Associated injuries and findings include bone bruises, fractures, meniscal tears, anterior subluxation of the tibia, and other ligament injuries.

Bone bruises typically are seen at the midlateral femoral condyle and posterior lateral tibial plateau (Fig. 25), although the location can vary, based on injury mechanism.[73]

An impaction fracture along the lateral femoral condyle, referred to as the ‘‘deep sulcus sign’’ (Fig. 26), typically measures more than 2 mm in depth before being a significant indicator of ACL tear.

A Segond fracture is an avulsion fracture involving the lateral tibial rim (Fig. 27). Classically, this injury was felt to represent an avulsion of the middle third of the lateral capsular ligament. The structure actually avulsed is under debate, and the injury may reflect avulsion of the iliotibial tract and anterior oblique band of the fibular collateral ligament.[74]

Usually, meniscal tears are located within the posterior horn of either the medial or lateral meniscus. Additional associated soft tissue injuries include damage to the medial collateral ligament (Fig. 28) and posterolateral corner structures.

Without the stability provided by the ACL, the tibia can sublux anteriorly with respect to the femur (Fig. 29), causing the ‘‘anterior tibial translocation sign’’.[75] More than 5 to 7 mm of anterior translocation has a high association with an ACL tear.[76,77] The anterior translocation of the tibia can cause the posterior horn of the lateral meniscus to be uncovered, and may also cause the PCL to buckle (Fig. 30). However, a buckled or J-shaped PCL can be seen with or without an ACL tear. Contour abnormalities of the normal PCL can be exaggerated if the patient is imaged in a hyperextended position.[12]

Figure 25: Bone contusions caused by partial-thickness ACL tear on sagittal fat-suppressed proton density MR imaging. High signal in the lateral femoral condyle (arrowhead) and posterior aspect of the lateral tibial plateau (arrow) are typical for the ‘‘kissing contusions’’ caused by a pivot shift knee injury.[12]

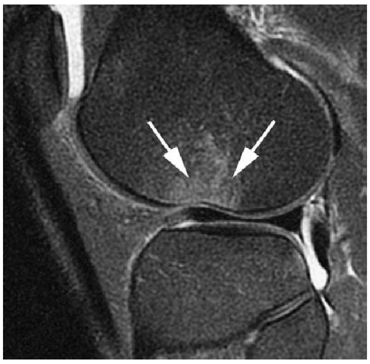

Figure 26: Deep sulcus sign on sagittal fat-suppressed T2-weighted MR imaging. An impaction fracture of the lateral femoral condyle with surrounding edema (arrows) was associated with a partial-thickness ACL tear.[12]

Figure 27: Segond fracture.

Figure 28: High-grade partial-thickness ACL tear (*) on coronal fat-suppressed T2-weighted MR imaging. Associated findings include medial collateral ligament tear (arrowheads), medial meniscus posterior horn tear (arrow), and multifocal bone contusions.[12]

Figure 29: Anteriorly subluxed tibia (black arrow) with respect to the posterior aspect of the femoral condyle (line) on sagittal fat-suppressed proton density MR imaging. A full-thickness ACL tear was present. A bone contusion (white arrow) is located in the posterior aspect of the lateral tibial plateau.[12]

Figure 30: A hooked, or J-shaped, PCL (arrow) is associated with a full-thickness ACL tear (not shown) on sagittal fat-suppressed proton density MR imaging.[12]

Atypical tears and pitfalls

Evaluating the ACL for injury has several potential pitfalls. A common pitfall of ACL imaging is volume averaging of the ligament with other structures in the intercondylar notch, including adjacent fluid, fat, and bone.

Close examination of the ligament in multiple planes can avoid this pitfall. Fibers of the ACL may be separated by thin lines of fat distally, so this should also not be confused with injury.

The ACL can undergo mucoid degeneration, mimicking a tear because of increased T2-weighted signal of the ligament fibers.[78,79] Degeneration, however, would not be associated with any secondary signs of injury.

Another cause of high signal within the ACL is the development of a ganglion cyst. The cause is unknown, but has been associated with prior trauma.[80, 81] These high T2-weighted signal cysts displace the normal tendon fibers and can be confused with an ACL tear. Ganglia and mucoid degeneration can coexist and are unrelated to instability.[82]

A final pitfall is that the ACL may be hypoplastic or absent, as a normal variant.[83]

Anterior cruciate ligament chronic injury

With conservative therapy, partial and complete ACL tears can regain continuity.[84, 85]

As the ACL heals, the increased T2-signal begins to resolve on MR imaging. Scar tissue can cause the ligament fibers to become thickened and indistinct, or the scar tissue can mask the signs of prior injury entirely.[86]

The ACL may form bridging scar tissue to the region of the intercondylar notch (Fig. 31) or PCL. Patients who have ACL-deficient knees may show abnormal anterior tibial subluxation,[87] which can worsen over time.[88] Although the ACL functions to restrain rotation, significant alterations in tibial rotation were not documented on a recent study evaluating ACL-deficient knees with MR imaging.[87]

Figure 31: Chronic full-thickness ACL tear on sagittal fat suppressed proton density MR imaging. The torn ACL (arrowhead) has adhered partially to the intercondylar notch roof (arrow).[12]

Posterior cruciate ligament acute injury

Typical tears and associated injuries

The PCL is injured less commonly than the ACL, but can demonstrate the same range of appearances on MR imaging, from focal areas of abnormal signal to complete disruption of the ligament. The PCL is evaluated best on sagittal MR images obtained with a fluid-sensitive sequence.

The PCL most commonly tears at the mid portion of the ligament (Fig. 32), and is more likely than the ACL to have a partial tear.[89] Regardless of the imaging modality used, it can be difficult sometimes to differentiate partial- from full-thickness tears.[90]

MR classification systems of tears have been proposed but are not used widely.[91] PCL injuries have a high association with other injuries.

Trabecular microfractures, or bone bruises, are seen commonly. The reported incidence ranges from 32% to 83%.[92, 93] Unlike the bone bruises associated with ACL tears, the bruises associated with PCL tears have a less predictable location, and can be located medially, laterally, or within the patella.[93]

Up to one half of PCL tears also have medial collateral ligament and meniscal tears.

Full-thickness PCL tears may be associated with posterior translation of the tibia with respect to the femur (Fig. 33) because of the lack of ligamentous support. PCL tears are associated with posterolateral corner injuries.[94]

Figure 32: Partial-thickness PCL tear seen as intermediate signal in the mid- (arrow) and proximal portions of the ligament on sagittal fat-suppressed proton density MR imaging.[12]

Figure 33: Full-thickness PCL tear (arrow) and posterior subluxation of tibia with respect to femur on sagittal fat-suppressed T2-weighted MR imaging.[12]

Atypical tears and pitfalls

A few unusual variants of PCL injury have been reported in the literature.

A ''peel-off'' PCL tear refers to a full-thickness tear along the femoral attachment, without an avulsion fracture. This tear has an arthroscopic option for repair.[95]

An avulsion fracture of the femoral attachment of the PCL has been seen with knee dislocation and popliteal artery rupture in a child.[96]

Isolated tears of the PMB can be seen as well.[97]

Finally, it is also somewhat unusual to have a PCL tear in the absence of other injuries, such as bone contusions, ligament strain or tear, or meniscal injuries.

Magic angle artifact can produce foci of increased T1-weighted signal within the PCL in the absence of injury or degeneration. The magic angle artifact will occur in any structure, usually a tendon or ligament, oriented 55 degrees to the main magnetic field. Because this MR artifact is limited to sequences with a short echo time, there will be no corresponding abnormal signal on proton density or T2-weighted sequences.

A ruptured PCL rarely can maintain a normal contour.[98]

Another potential pitfall is the ‘‘double PCL sign’’ caused by a displaced bucket-handle tear of the medial meniscus. The displaced meniscal tissue can lie parallel to the PCL on a sagittal image and should not be confused with a PCL injury.[12]

Posterior cruciate ligament chronic injury

As with the ACL, partial- or full-thickness PCL tears may regain continuity of the ligament fibers with only conservative therapy.[84] When a PCL injury consists of a focus of increased T2-weighted signal within a continuous ligamentous band, conservative therapy can be considered.

Patients with this MR appearance have preserved or improving joint stability over time.[99,100] After injury and subsequent healing, the PCL may return to homogeneous, normal, low signal intensity on MR imaging. The chronically injured PCL may be thickened or elongated (Fig. 34).

The PCL-deficient knee may show abnormal posterior subluxation of the tibia with respect to the femur, up to 44% of which cannot be reduced using anterior force.[101] The ACL can be weakened by chronic PCL injury, resulting in decreased diameter, size, and number of collagen fibrils.[102]

Figure 34: Chronic PCL tear on sagittal fat-suppressed T2-weighted MR imaging. After partial-thickness tear 3 years prior, the PCL (arrows) has healed with an elongated, undulating contour. The tibia is subluxed posteriorly with respect to the femur.[12]

Meniscal Injury

Meniscal extrusion

Meniscal extrusion is measured from the outer meniscal edge to the proximal tibial margin. Extrusion of the medial meniscus more than 3 mm is considered abnormal (Fig. 35). This degree of extrusion can be seen in patients who have advanced meniscal degeneration, and various types of meniscal tears.(103)

Although extrusion of the anterior horn or body of the lateral meniscus sometimes is considered a normal variant,(104) others consider extrusion of the lateral meniscus more than 1 mm to be abnormal.(105) Damage to the meniscus and meniscal extrusion can be associated with cartilage abnormalities and likely predisposes to the development of osteoarthritis.(103,106)

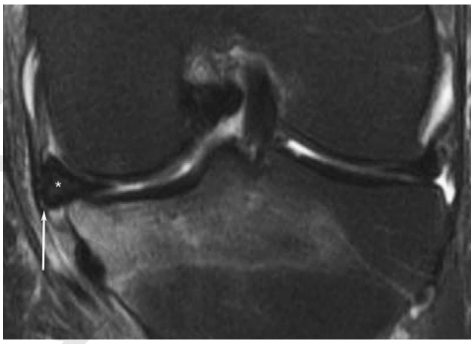

Figure 35: Coronal FSE T2-weighted fat-saturated image demonstrating medial extrusion (arrow) of the body of the medial meniscus (asterisk) because of a posterior medial meniscal root tear. Bone contusion is also seen in the medial tibial plateau, with cartilage loss in the medial femoral condyle.(25)

Etiology of Meniscal tears

The cause of meniscal tears can be divided into two categories: Increased force on a normal meniscus, usually resulting in longitudinal or radial tears, and normal forces on a degenerative meniscus, usually producing horizontal tears in the posterior half of the meniscus.(107)

Tears are more common in the medial meniscus,(18,22) possibly because the medial meniscus is less mobile, and it bears more force during weight-bearing than the lateral meniscus,(103,108) with 56% of tears involving the posterior horn of the medial meniscus.(109) Tears isolated to the anterior two thirds of the meniscus are uncommon, representing only 2% of medial and 16% of lateral meniscal tears.(110)

Lateral meniscal tears are more common in younger patients (under 30 years old), who have a higher incidence of tears related to sporting events than do older patients. It is likely that this is related to the higher incidence of concomitant ACL tears in this population.(111) The prevalence of meniscal tears increases with age,(18) with degenerative tears also more common in older patients.(111)

Diagnosis of Meniscal tears

Many MR sequences have been used to evaluate for meniscal tears, and although they vary in other parameters, they all share a short echo time (TE).(112)

The advantages of a short TE include a reduction in scan time, decreased susceptibility and fewer flow artifacts, an ability to acquire more scan slices per sequence, and an improved signal-to-noise ratio.

The most commonly used sequences include spin-echo or fast spin-echo (FSE) proton density with or without fat saturation, T1, and gradient echo (GRE).(112)

The normal meniscus has low signal on all MR imaging sequences. On sagittal MR images, the anterior and posterior horns of the lateral meniscus are nearly equal in size, whereas the posterior horn of the medial meniscus is larger than the anterior horn.

The diagnostic criteria for a meniscal tear in a knee without prior meniscal surgery is either an area of abnormal signal within the meniscus on at least one image that extends to the meniscal articular surface, or abnormal morphology of the meniscus.(110)

The sagittal plane is used most commonly to evaluate meniscal pathology; however, studies have reported that the coronal imaging plane improves the detection and characterization of radial, bucket-handle, horizontal, and displaced tears of the meniscal body, (113, 114) and that the axial plane assists in diagnosing radial, vertical, complex, displaced, and lateral meniscal tears.(115,116)

An accurate description of a meniscal tear has become increasingly important, with the emphasis on meniscal preservation and repair,(17,109,117,118) because of the known, long-term complications of complete meniscectomy.

The description should include whether the tear is in the posterior horn, body, or anterior horn, and whether the tear is in the peripheral third of the meniscus (roughly corresponding to the vascularized red zone), the inner two thirds of the meniscus, or both.

It should also be stated if the tear is complete, extending from one articular surface to another, or incomplete. The tear should be described as horizontal, vertical (longitudinal, radial, or parrot-beak), or complex.

The length of the tear is also important because it may determine if the tear is repairable.(109)

Classification of tears

Horizontal tears

Horizontal or cleavage tears are parallel to the tibial plateau and divide the meniscus into upper and lower segments (Figs. 36 and 37).[109]

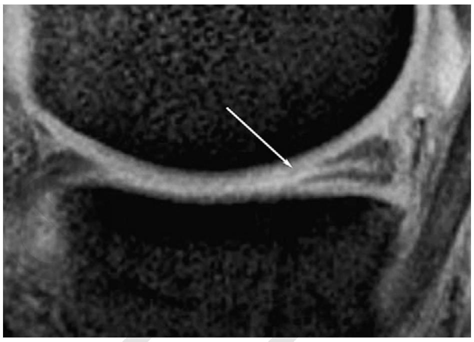

Figure 36: Sagittal GRE image demonstrating a horizontal tear (arrow) of the posterior horn of the medial meniscus.[25]

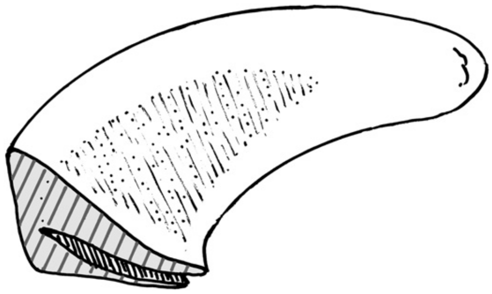

Figure 37: Horizontal tear.[25]

Vertical tears

Vertical longitudinal tear occurs between the circumferential collagen fibers, parallel to the long axis of the meniscus, perpendicular to the tibial plateau, with the tear equidistant from the peripheral edge of the meniscus (Figs. 38). [109]

A vertical radial tear occurs on a plane perpendicular to the long axis of the meniscus and perpendicular to the tibial plateau. [109, 119, 120] These tears traverse the circumferential collagen fibers, resulting in either two separate pieces of meniscus, or a single portion of meniscus attached to the tibia in only one location. [119, 120]

These tears disrupt the ability to distribute the hoop stresses associated with weight-bearing, and usually are not repairable. [17]

Partial thickness radial tears can be debrided, but the meniscus is unlikely to regain full function and likely will displace peripherally and allow contact between articular cartilage surfaces, resulting in accelerated degenerative changes.[17,112,119,120]

As a result, even small radial tears can have a significant detrimental effect on the function of the meniscus, and can cause pain.[17,121]

The prospective detection of radial tears is reported to be as low as 37%; however, using four signs (ghost, cleft, truncated triangle, and marching cleft), the sensitivity for the detection of radial tears is reported to be 89%.[17]

A radial tear can have a ghost appearance if there is either an absent section of meniscus or an area of high signal in the shape of the meniscus on a single image that is parallel to the tear.

A marching cleft presents most commonly with a radial tear at the junction of the posterior horn and body that appears to ‘‘move’’ across the meniscus on successive images. The truncated triangle sign is noted when there is an abrupt truncation of the inner point of the normal meniscus.

The cleft sign occurs when there is abnormal signal present in the meniscus perpendicular to the imaging plane (Figs. 39).[17]

Vertical parrot-beak tears are radial at the inner meniscal edge and longitudinal more peripherally within the meniscus.[109,120] These tears are difficult to detect with MR imaging, with reported sensitivities ranging from 0% to 60% (Fig. 40).[109]

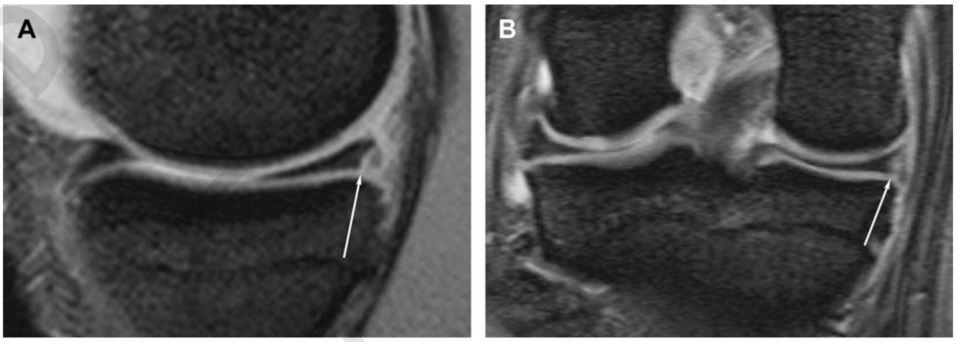

Figure 38: **(A)** Sagittal GRE image demonstrating a peripheral vertical longitudinal tear (arrow) of the posterior horn of the medial meniscus.

(B) Coronal GRE image demonstrating a peripheral vertical longitudinal tear (arrow) of the body of the medial meniscus.[25]

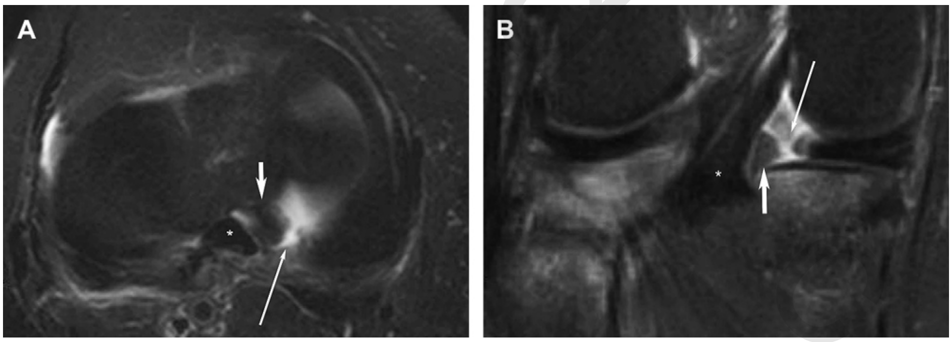

Figure 39: **(A)** FSE T2-weighted fat-saturated axial image demonstrating a radial tear (thin arrow) of the posterior horn of the medial meniscus near the posterior meniscal root attachment (thick arrow). Note the proximity of the PCL (asterisk) to the posterior root attachment of the posterior horn of the medial meniscus.

(B) FSE T2-weighted fat-saturated coronal image demonstrating a radial tear (thin arrow) in the posterior horn of the medial meniscus with the cleft sign. The posterior medial meniscal root is intact (thick arrow). Note the proximity of the PCL (asterisk) to the posterior root attachment of the posterior horn of the medial meniscus.[25]

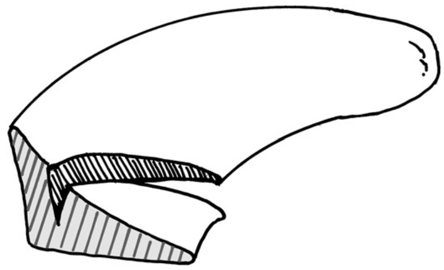

Figure 40: Vertical parrot-beak tear [25]

Complex tears

Complex tears either have two or more tear configurations or are not categorized easily into a certain type of tear.[109]

Bucket-handle tears

A bucket-handle tear results when the inner meniscal segment of a longitudinal or oblique tear ‘‘flips,’’ most commonly into the intercondylar notch. This often involves the entire meniscus but can involve only the posterior horn and body or a single horn of the meniscus.[122]

The inner flipped portion of the meniscus can remain intact or it can be disrupted.

The MR diagnosis of a bucket-handle tear uses many signs. The double PCL sign consists of meniscal material in the notch, inferior and parallel to the PCL in the same sagittal plane.[122]

The fragment in notch sign occurs when a fragment of meniscus is in the notch but not in the same sagittal plane as the PCL (Fig. 41). It is seen more often in lateral bucket-handle tears.[122]

The absent bow tie sign is diagnosed when the meniscus body is not identified on at least two adjacent sagittal 4 to 5 mm-thick images. False positives with this sign can occur in children or small adults, in degenerative menisci, in radial tears, and with postsurgical changes.[112,123]

The disproportional posterior horn sign is present when there is a larger posterior horn on sagittal images closer to the root attachment than peripherally, presumably because of a centrally displaced fragment of the more peripheral posterior horn.

A quadruple cruciate sign can be observed if there are medial and lateral bucket-handle meniscal tears, with both fragments displaced into the notch (Fig. 42).[124]

The flipped meniscus sign, occurs when the fragment is flipped anteriorly adjacent to the ipsilateral anterior horn.[122] The anterior horn should not measure greater than 6 mm in height; if it does, this should be considered.

The double anterior horn sign is the same as the flipped meniscus sign; however, two separate ‘‘anterior horns’’ are identified (Fig. 43). Usually, the flipped meniscus and double anterior horn signs are associated with intercondylar meniscal displacement.[122]

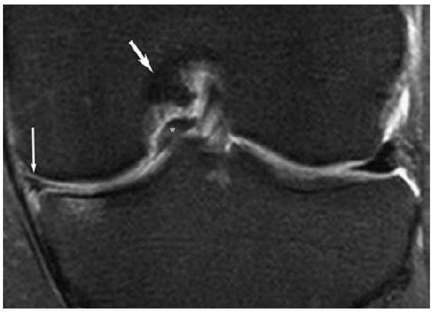

Figure 41: FSE proton density–weighted fat-saturated coronal sequence demonstrating a bucket-handle tear of the medial meniscus, with a portion of the body of the medial meniscus located in the intercondylar notch (asterisk) beneath the PCL (thick arrow) and adjacent to the ACL. Note the remainder of the body of the medial meniscus is truncated (thin arrow).[25]

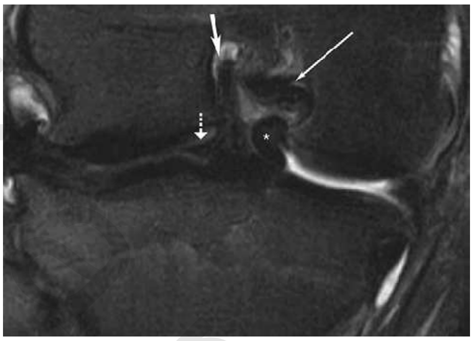

Figure 42: FSE T2-weighted fat-saturated coronal image demonstrating bucket-handle tears of both menisci, with fragments from both meniscal bodies flipped into the intercondylar notch. The fragment of the medial meniscus (asterisk) is inferior to the PCL (thin arrow) and the fragment of the body of the lateral meniscus (dotted arrow) is adjacent to the ACL (thick arrow), producing the ‘‘quadruple cruciate sign.’’ [25]

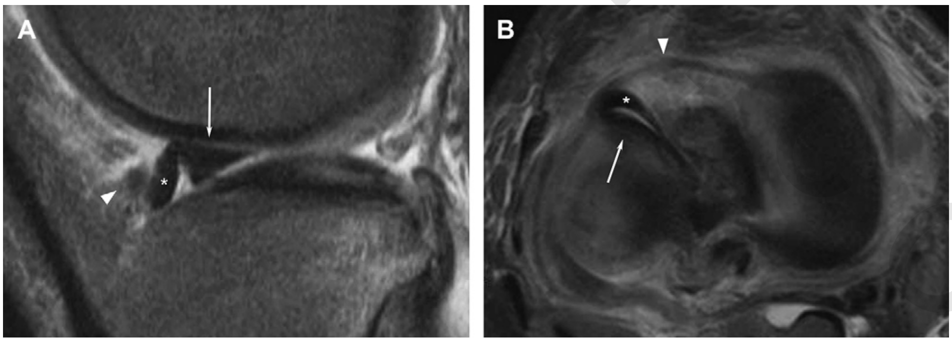

Figure 43: **(A)** Sagittal FSE proton density–weighted fat-saturated image demonstrating a tear of the lateral meniscus, with the fragment of the body (long arrow) flipped adjacent to the anterior horn (asterisk). Note the anterior transverse intermeniscal ligament (arrowhead). **(B)** Axial FSE proton density–weighted fat-saturated image demonstrating flipped fragment of lateral meniscus body (long arrow) adjacent to the anterior horn of the lateral meniscus (asterisk). Note bowing of the anterior transverse intermeniscal ligament (arrowhead).[25]

Flap tear with displacement

A flap tear or a displaced flap tear is a term that is used often to describe a short-segment, horizontal meniscal tear with fragments either displaced into the notch or into the superior or inferior gutters (Fig. 44).[122, 125]

These tears are unstable[125] and are important to recognize and describe, especially if the flap of meniscal tissue extends into the inferior gutter because this is a difficult area for the surgeon to visualize (Fig. 45).[126]

This tear can be suspected when the normal rectangular meniscus is not identified on the most peripheral sagittal image, and meniscal tissue is noted inferior to the body segment.[126] The coronal images are the most useful in confirming the inferiorly displaced meniscal tissue.

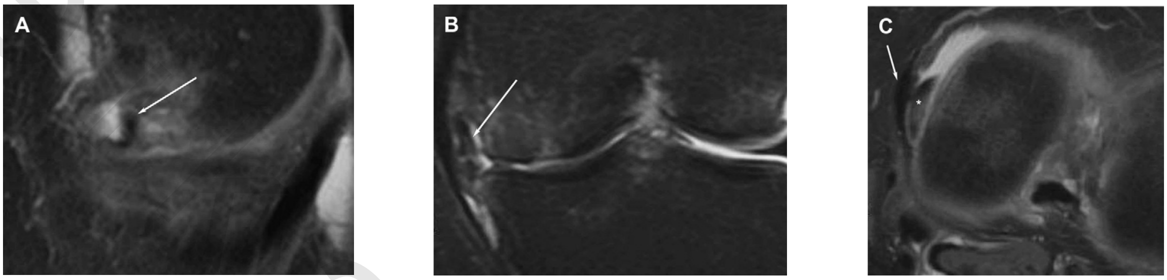

Figure 44: (A) FSE proton density–weighted fat- aturated sagittal image demonstrating a flap of meniscal tissue (arrow) extending from the anterior horn body junction of the medial meniscus into the superior recess medially.

(B) Coronal short tau inversion recovery (STIR) image demonstrating the flap of meniscal tissue (arrow) extending into the superior aspect of the medial recess. Medial compartment chondromalacia is also noted.
(C) FSE PD–weighted fat-saturated axial image demonstrating a flap of meniscal tissue (asterisk) deep to the MCL (arrow) and superficial to the medial femoral condyle in the superior aspect of the medial recess.[25]

Figure 45: GRE coronal image demonstrating truncation of the body of the medial meniscus (truncated triangle sign), with the flap of meniscal tissue flipped under the meniscus into the inferior recess medially (arrow).[25]

Free fragments

Free fragment displacement is rare, occurring in 0.2% of symptomatic meniscal lesions. [122]

Root tears

A root tear occurs at the tibial attachment or ''root'' of the meniscus, and it has been described only posteriorly (Fig. 46).[105]

Studies have described an association between extrusion of the medial meniscus, medial compartment arthritis, and posterior medial meniscal root tears.[105,120]

A root tear is reportedly a difficult tear to diagnose because meniscal tissue is noted only on one side of the tear. The diagnosis is easier to make medially because of the close anatomic relationship between the posterior horn of the meniscus and the tibial attachment of the PCL.

Normally, on 3-mm sagittal images, the meniscus should be seen on the image medial to the PCL attachment; otherwise, a root tear is suspected and the coronal images can confirm.[120] Meniscal extrusion is more pronounced and nearly four times as common with medial, as opposed to lateral, meniscal root tears.[105]

Lateral meniscal root tears are diagnosed when the posterior horn of the lateral meniscus does not cover the most medial aspect of the posterior lateral tibial plateau on at least one coronal image.[120]

In the setting of an ACL tear, the lateral meniscal root is torn more than three times as often as the medial root, with lateral meniscal extrusion greater than 1 mm present in 23% of patients who have lateral root tears and in 2% of those who have intact lateral meniscal roots.

All patients who had meniscal extrusion but intact roots had another type of meniscal tear, with 60% having radial or complex tears. Extrusion was noted nearly four times as often in lateral meniscal root tears if the meniscofemoral ligaments were absent.[105]

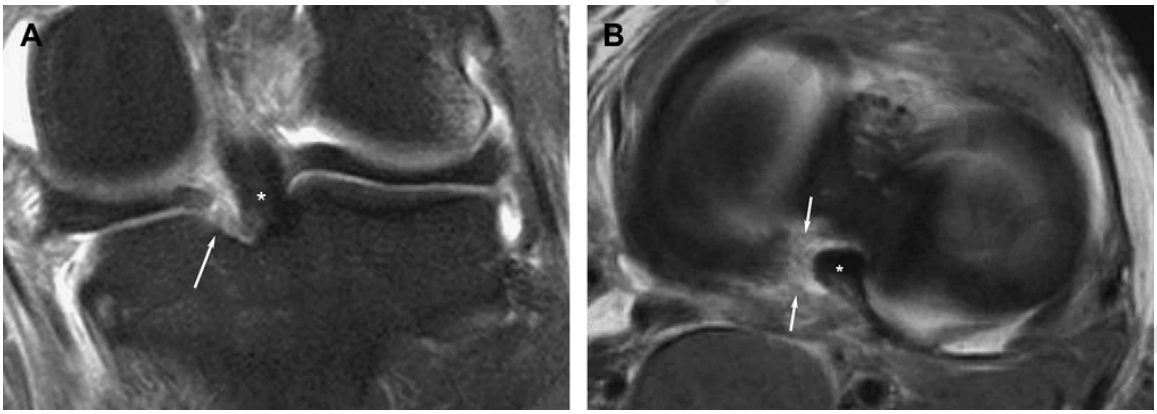

Figure 46: **(A)** FSE proton density–weighted fat-saturated coronal image demonstrating a tear of the posterior medial meniscal root (arrow). Note the tibial attachment of the PCL (asterisk). **(B)** Axial FSE proton density–weighted fat-saturated image demonstrating a tear of the posterior medial meniscal root (arrows). Note the proximity to normal tibial attachment of PCL (asterisk).[25]

Meniscal tears in the setting of anterior cruciate ligament tears

In the setting of an acute ACL injury, the lateral meniscus is torn twice as often as the medial meniscus, with approximately one half representing peripheral longitudinal tears most commonly located in the posterior horn of the lateral meniscus.

In ACL-deficient knees, the increased shear forces on the less mobile posterior horn of the medial meniscus may account for the increased rate of medial meniscal tears, which possibly is related to the increased posterior translation of the femur in relation to the tibia with flexion in ACL-deficient knees.[(18)]

These tears are often less amenable to repair; therefore, early ACL repair in certain populations (athletes and manual laborers) should be considered. [(18)]

Meniscal pitfalls

Seventy percent of false-positive MR imaging findings occur in the posterior horns of the menisci, which are the most difficult areas to evaluate at arthroscopy.[(110, 127-129)]

The standard arthroscopic technique for evaluating the posterior horn of the medial meniscus is to probe the tibial surface while compressing the femoral surface.[(127)]

Because evaluation of the meniscal gutters is also difficult, the accuracy of arthroscopy for diagnosing meniscal tears is 69% to 98%, depending on the arthroscopist and the location and type of tear.[(128)]

Therefore, some of the cases considered false positives on MR imaging might, in fact, represent false negatives on arthroscopy.

False positives can also occur with healed meniscal tears or postoperative menisci, in which abnormal signal extending to the surface remains on standard MR imaging sequences.[(110,127)]

False positives because of magic angle phenomenon on sequences with a TE less than 37 ms can also occur in the posterior horn of the lateral meniscus because of the central upsloping of the meniscus.[(130)]

Truncation artifact can also be a cause of false positives; however, the use of a matrix of at least 192 x 256 minimizes this artifact such that it is seen rarely today.[(131)]

Radially orientated collagen ‘‘tie’’ fibers, which have linear intermediate signal within the meniscus, and myxoid degeneration can also simulate tears.[(19)]

Abnormal signal having a speckled or spotty appearance on T1 and proton density images can occur in the anterior horn of the lateral meniscus near the central attachment on the most central sagittal images,[(112)] thought to be caused by high signal striations from the ACL fibers. [(132)]

Sometimes, the transverse intermeniscal ligament can simulate a tear in the anterior horns of either menisci.[(21,133)]

The lateral inferior genicular artery can simulate a tear of the lateral meniscus, and the normal concavity of the peripheral aspect of the meniscus can mimic a horizontal tear on peripheral sagittal images caused by a volume-averaging artifact.[(133)]

The meniscal attachments of the meniscofemoral ligaments can simulate a tear in the posterior horn of the lateral meniscus.[(134)]

The popliteus tendon adjacent to the posterior horn of the lateral meniscus can also be a source of error because of fluid tracking along the intraarticular portion of the tendon.[24,133]

The medial and lateral oblique meniscomeniscal ligaments and [135] the anterior meniscofemoral ligament of the medial meniscus [136] can also simulate tears.

However, following these structures on multiple images, evaluating the meniscus in different imaging planes, and having a thorough understanding of the anatomy often can prevent these errors.

Meniscal contusion can demonstrate abnormal amorphous or globular meniscal signal that contacts an articular surface but is less discrete and less well defined than the signal associated with a tear and intrasubstance degeneration, respectively. All patients have adjacent bone contusions and most have ACL tears. The abnormal signal can resolve over time.[137]

The diagnostic accuracy of MR imaging for meniscal tears decreases in patients who have chondrocalcinosis because the calcium deposits may demonstrate high signal on T1-weighted, intermediate- weighted, and short tau inversion recovery (STIR) sequences.[138]

Reviewing radiographs can alert the radiologist to the chondrocalcinosis. In addition, most meniscal tears are more linear than the signal abnormalities seen with chondrocalcinosis; however, there is overlap.[112]

Meniscocapsular separation

Meniscocapsular separation occurs when the meniscus detaches from the capsular attachments,[139] which is more common medially and usually is associated with other injuries.[140]

The medial capsuloligamentous structures can be thought of as three layers, from superficial to deep: layer 1: crural fascia; layer 2: superficial portion of the MCL; and layer 3: capsule and deep portion of the MCL.[141]

The medial meniscus is attached to the femur by way of the meniscofemoral ligament, and to the tibia by way of the coronary (meniscotibial) ligament, which are extensions of the deep fibers of the MCL.[141]

Meniscocapsular separation is evaluated best on coronal and sagittal T1- or proton density–weighted sequences for anatomy, and fat-saturated T2-weighted or STIR sequences for pathology.[141]

Signs that have been described in meniscocapsular separation include displacement of the meniscus relative to the tibial margin, extension of the tear into the superior or inferior corner of the peripheral meniscus, and an irregular outer margin of the meniscus body on coronal images.

Additional signs include increased distance between the meniscus and the MCL, or fluid between the meniscus and the MCL.[140,141]

The presence of perimeniscal fluid and an irregular meniscal outline are the best predictors of meniscocapsular separation (Fig. 47).[141]

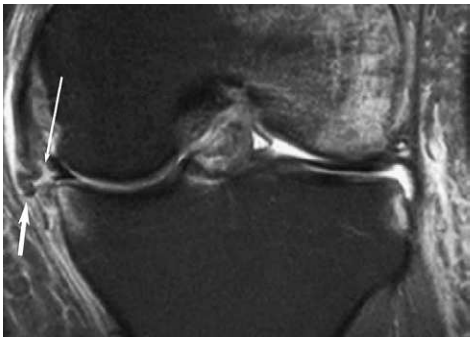

Figure 47: FSE proton density–weighted fat-saturated coronal image demonstrating fluid signal and widening (thin arrow) between the medial edge of the body of the medial meniscus and the MCL, consistent with meniscocapsular separation. Note the complete disruption of the tibial attachment of the MCL (thick arrow).[25]

Findings associated with meniscal tears

A torn or absent superior popliteomeniscal fascicle was noted in 31% of patients with, and 4% without, lateral meniscal tears.[142]

Presumptive subarticular stress reactions of the knee are characterized by an edema-like pattern in the subarticular marrow, which encompasses a focal, linear, or curvilinear low-signal area. Of these patients, 76% have a meniscal tear in the same compartment.

These lesions occur in a much older population and likely are caused by radial or root tears that predispose the knee to increased stress which, in an older population, results in insufficiency- type lesions.[143] The lesions have a similar appearance to spontaneous osteonecrosis of the knee, which is a reported complication of radial tears, especially in older patients with large body habitus,[120] and in patients who have had a prior medial meniscectomy or degenerative medial meniscal tears.[144,145]

Subchondral bone contusions involving the posterior margin of the medial tibial plateau in patients who have ACL tears are associated with posterior horn medial meniscal tears and meniscocapsular separation/injury.

The mechanism is thought to be a contrecoup impaction injury, with 62% of the medial meniscal tears in the far peripheral 20% of the meniscus. Lateral meniscal tears were also noted in 36% of these patients.[146]

Meniscal cysts

Meniscal cysts are located twice as often medially, and may be lobulated or septated in appearance.[112,147,148]

The cysts can be confined within the meniscus (intermeniscal) or can extend into the adjacent soft tissue (perimeniscal), with the latter more common.[149]

The most widely accepted cause of a meniscal cyst is extension of fluid through a meniscal tear.[147,149]

Medially, the cysts are adjacent to the posterior horn, with anterior extension adjacent to the body (Fig. 48).[147,148]

Laterally, the cysts are adjacent to the anterior horn, with posterior extension adjacent to the body in 54% of cases. Direct communication between the meniscal cyst and the meniscal tear is noted in 98% of cases.

Lateral meniscal cysts more often present as palpable masses, likely because of the thinner, overlying, lateral soft tissues.(147)

Occasionally, a posterior horn medial meniscal tear can produce a cyst that extends centrally within the joint adjacent to the posterior central aspect of the PCL or surrounding the PCL, simulating a ganglion.(149)

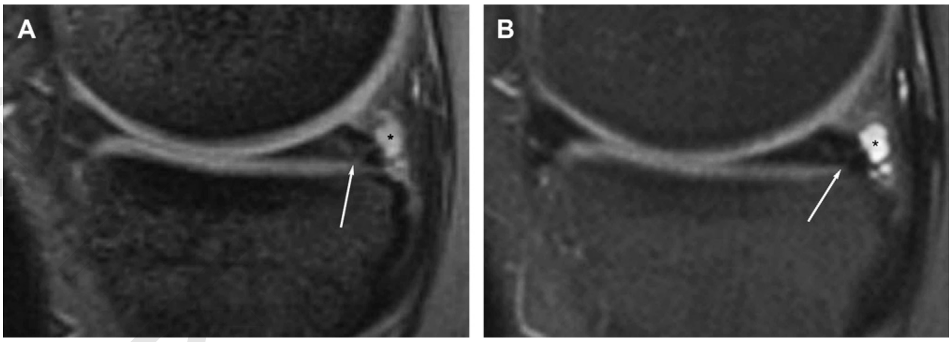

Figure 48: **(A)** GRE sagittal image demonstrating a perimeniscal cyst (asterisk) adjacent to the posterior horn of the medial meniscus, with the tear (arrow) extending to the cyst.

(B) FSE proton density–weighted fat-saturated sagittal image demonstrating a perimeniscal cyst (asterisk) adjacent to the posterior horn of the medial meniscus, with the tear (arrow) extending to the cyst.(25)

Cartilage Lesions

Articular cartilage lesions may be categorized as degenerative or traumatic in cause.(150)

Early degenerative disease may be seen on MRI as early alterations in cartilage contour morphology (fibrillation, surface irregularity); changes in cartilage thickness, including cartilage thinning or thickening, which may be an early feature predating cartilage volume loss; or intrachondral alterations in signal intensity potentially related to premorphologic intrasubstance collagen degeneration and increased free-water content.(150)

Advanced degenerative chondral lesions typically manifest on MRI as multiple areas of cartilage thinning of varying depth and size, usually seen on opposing surfaces of an articulation.(150)

Cartilage defects typically illustrate obtuse margins and may be associated with corresponding subchondral regions of increased T2-weighted signal reflective of subchondral edema or cysts or low signal intensity reflective of subchondral fibrosis or trabecular sclerosis.(150)

Other associated MRI findings of degenerative cartilage disease include central and marginal articular osteophytes, joint effusion, and synovitis.(150)

In contrast, traumatic chondral lesions generally manifest on routine clinical MRI as solitary focal cartilage defects with acutely angled margins (Fig. 49).(150)

Traumatic chondral injuries are typically the result of shearing, rotational, or tangential impaction forces and often result in high-grade partial- or full-thickness cartilage tears or in osteochondral injuries of cartilage and the underlying subchondral bone.(150)

Linear cartilage clefts or fissures may also be seen, and they can extend for variable depths within the articular cartilage and may result in chondral flap lesions or delamination injuries.(150)

Associated alterations in subchondral marrow signal, including bone bruising, bone edema, or subchondral fracture, may be helpful signs in delineating areas of overlying cartilage injury.(150)

The finding of a focal signal change in the subchondral bone marrow should encourage careful evaluation of possible overlying hyaline articular cartilage injury or disease. In general, delaminating injuries, superficial flap tears, and surface fibrillation are the most difficult lesions to visualize and assess accurately with MRI.(150)

When a traumatic cartilage lesion is identified, its description should include the location, size, and depth of the lesion and the presence or absence of associated chondral fragments. (150)

Traumatic cartilage fragments may remain in situ, become partially detached, or become loose and displace into the joint space. As a result, recognition of a traumatic chondral defect should prompt careful inspection of the joint for a displaced intraarticular chondral body.(150)

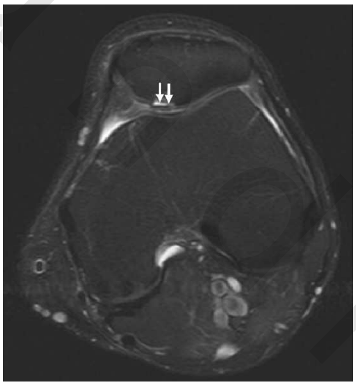

Figure 49: 40-year-old woman with acute knee injury.

Axial fast spine echo image shows chondral fracture (arrows) with mild displacement of chondral fragment.(150)

Management of internal derangement

Anterior cruciate ligament reconstruction

The ACL can be reconstructed using various materials and techniques. Autograft tendon, allograft tendon, or synthetic materials may be used.

Autograft materials, using the central third of the patellar tendon, with attached bone, or the distal hamstring tendon, are used most widely.

The use of synthetic grafts has fallen out of favor because of high complication and failure rates.(151) Reconstruction of the ACL-deficient knee is recommended within 1 year of injury to reduce the incidence of secondary meniscal tears and degenerative change.(152,153)

Single-bundle/double-bundle technique

Traditional ACL reconstruction functionally replaces only the AMB of the ACL.

The double-bundle technique of ACL repair involves placement of double ligament, using up to four bone tunnels. The surgical technique used for a double-bundle repair varies, including location of the access portals, type of fixation device, placement of bone tunnels, number and size of tunnels, and intra-operative position of the knee.[154]

Allograft and autograft materials can be used. Occasionally, a single native bundle and a single reconstructed bundle are seen in a single-bundle reconstruction.[154]

Normal ACL Graft Reconstruction

The most commonly used methods are bone–patellar tendon–bone and hamstring autografts.

The use of the middle one-third of the patellar tendon, with bone plugs attached to each end, has historically been considered the reference standard for ACL graft reconstruction because of the inherent strength and stiffness of the graft.[155]

However, subsequent patellar-tendon abnormalities and anterior knee pain are relatively common complications with this type of graft.

A four-strand hamstring graft often is made of segments from the semitendinosus tendon, the gracilis tendon, or both. The tendon segments are folded and braided together to form a quadruple thickness strand, which is then fixed to the femur and tibia.[155]

The hamstring graft became popular because of the low reported morbidity related to the graft harvesting site. However, hamstring grafts traditionally have been subject to slippage. New fixation techniques seem to have addressed this problem.[156,157]

Proper fixation of the graft with interference screws, endobuttons, a screw-washer construct, or staples is crucial to avoid changes in the graft position during the initial postoperative incorporation period. Interference screws commonly are used as fixation devices in bone–patellar tendon–bone graft reconstruction.[158]

Positioning of the femoral and tibial tunnels is of paramount importance for proper function of the ACL graft. Accurate location of the femoral tunnel is essential to achieve isometry of the ACL graft.[158] Isometry refers to adequate constancy in length and tension of the graft during the complete range of knee motion (from flexion to extension).[158]

Over-the-top placement is not isometric; it results in increased graft length and tension as the knee is extended (Fig. 50a). If the femoral tunnel is placed too far anteriorly, the length and tension of the graft greatly increase as the knee is flexed (Fig. 50b).[158]

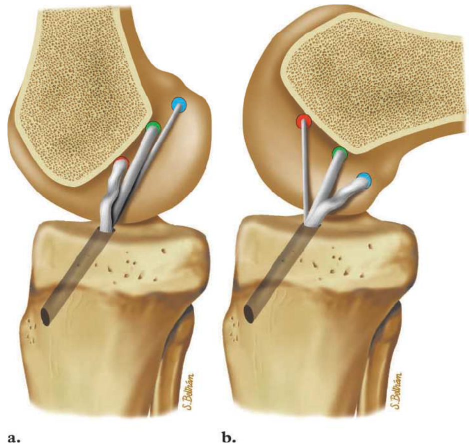

Figure 50: Effects of femoral tunnel placement on graft length and tension. Diagrams of the knee in extension (a) and flexion (b) show anterior (red circle), isometric (green circle), and over-the-top (blue circle) positions of the femoral tunnel site in ACL reconstruction.[155]

The femoral tunnel should be placed as far posteriorly as possible without disrupting the posterior cortex of the femur. Ideally, a 1–2-mm-thick cortical rim should remain.

On coronal images, the femoral tunnel should open superiorly above the lateral femoral condyle at the 10–11-o'clock position in the right knee and the 1–2-o'clock position in the left knee (Fig 51). [159, 160]

The tibial tunnel should be oriented parallel to the projected slope of the intercondylar roof (the Blumensaat line). In the sagittal plane, the opening of the proximal tibial tunnel should be posterior to the intersection of the Blumensaat line and the tibia.[155]

In the coronal plane, the tibial tunnel should open at the intercondylar eminence. At the time of surgery, the knee is extended while 1 cm of the drill bit is left protruding from the tibial tunnel into the joint. If roof impingement is present, anterior notchplasty may be performed.[155]

In notchplasty, a few millimeters of bone are removed from the anterolateral aspect of the intercondylar roof. [161] Care must be taken to avoid removing cortical bone superiorly in the femoral notch so as not to decrease contact of the patellofemoral joint surfaces during knee flexion. In addition, a tibial interference screw may be placed along the anterior aspect of the graft to correct roof impingement intraoperatively.[155]

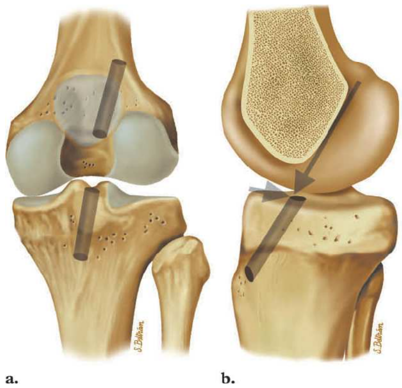

Figure 51: Correct positioning of the femoral and tibial tunnels in ACL reconstruction. **(a)** Diagram shows correct positioning of the tunnels in the coronal plane. In the left knee, the femoral tunnel should open superiorly at the 1–2-o'clock position. **(b)** Diagram shows correct positioning of the tunnels in the sagittal plane. The tibial tunnel should open posterior to the intersection of the Blumensaat line and the tibia (arrows).(155)

Posterior cruciate ligament reconstruction

Most PCL tears are partial thickness, as opposed to full thickness, and can be treated with conservative therapy. In some cases, the partially torn PCL can be repaired directly. Metal artifact and fibrous tissue can obscure the repair site.

For those injuries needing reconstruction, the materials used are similar to those for ACL reconstruction. Single- bundle or double-bundle reconstruction techniques can be used.(162)

Normal Appearance and failure

The normal appearance of the reconstructed PCL is somewhat controversial in the literature. The PCL graft likely undergoes a normal postoperative change in signal intensity similar to ACL grafts, although this change is not accepted uniformly.(163)

Thickening of the PCL graft is normal in the postoperative period. PCL graft failure has a similar appearance to ACL graft failure. Intermediate T2-weighted signal within the graft, excluding the 4- to 8-month postoperative period, suggests partial-thickness tearing.

Disruption of the graft fibers with interposed fluid signal intensity indicates full-thickness tearing.(163)

Management of meniscal tears

The four main options for treating meniscal tears are complete meniscectomy, partial meniscectomy, meniscal repair, and conservative treatment without meniscal surgery.(109)

The treatment of meniscal lesions depends on many factors, including the type, location, and size of the tear. Initially, meniscal lesions were treated with complete meniscectomy because the importance of the meniscus and its function were not understood well.(164,165) Unfortunately, complete meniscectomy has been shown to result in accelerated cartilage loss and the development of osteoarthritis.(164-167)

Partial meniscectomy is less damaging to the joint and is preferred to a complete meniscectomy in patients who have unstable tears,[18] when a primary meniscal repair is not possible.[109] Preservation of as much of the meniscus as possible, especially the outer third, and removing only unstable tissue, is the desired result; usually, however, some stable tissue is resected to approximate the original meniscal shape, in an attempt to reduce the inevitable increased stress on the remaining meniscal tissue.[164]

Many studies have shown progressive, long-term wear on the joint after partial meniscectomy, with a declining number of patients reporting excellent or good results over time.[166] This result is possibly because of the altered biomechanics of the meniscus, with the decreased ability of the meniscus to transmit hoop stresses, thereby resulting in increased stress on the remaining meniscus, additional tears, and accelerated degenerative change.[168]

As a result, meniscal repair has become more common, to maintain as much of the normal biomechanical function of the meniscus as possible.[169] Repairable meniscal tears usually are unstable, peripheral, longitudinal, or oblique tears. An unstable tear is one where the entire tear or a portion thereof can be displaced into the joint space. Radial, horizontal, or complex tears usually are not amenable to repair.[169]

After meniscal repair, patients are kept non- or partially weight bearing for several weeks, in contrast to partial meniscectomy, after which patients can resume full weight bearing much more quickly.[109]

Healing usually takes 4 months and once the tear heals, patients are usually asymptomatic. The long-term success of meniscal repairs varies from 67% to 92%, depending on the type and location of the tear.[18]

Factors that predispose to a favorable repair outcome include surgery within 8 weeks of injury, patient age under 30 years, tear length less than 2.5 cm, a peripheral tear, a lateral meniscus tear, and concomitant ACL reconstruction.[109]

Therefore, an accurate description of meniscal tears as repairable and irreparable has significant clinical implications, especially for athletes, because continued stress on a potentially repairable tear might make it irreparable.[109] Tears in the peripheral, vascularized portion of the meniscus can heal from an ingrowth of capillaries and eventually resemble fibrocartilage.[118,164]

Many of these tears may heal spontaneously and not require arthroscopy.[127] Longitudinal tears greater than 7 to 10 mm in length, especially post traumatic vertical peripheral tears, may heal if they are stable.[164] Some surgeons may not operate on horizontal or oblique partial-thickness tears,[170] and if a partial meniscectomy is performed on one of these tears, only the unstable portions may be removed, leaving a horizontal defect extending to the articular surface.[164]

In patients who have both lateral meniscal and ACL tears, the tear is typically in the periphery of the posterior horn or at the posterior root, and it is important to report if the tear extends anterior to the popliteus hiatus because tears posterior to the hiatus will not always be repaired.

Autologous meniscal transplantation has become more common, especially in younger patients who have had prior partial meniscectomy or who have irreparable meniscal tears.[164]

Other appropriate candidates are those with mild to moderate single-compartment cartilage degeneration, those with progressive loss of meniscal tissue but an appropriate varus/valgus alignment, and those having an ACL repair in which a meniscal transplant might improve stabilization.[171,172]

Often, meniscal transplantation is performed concomitantly with other procedures, including cruciate ligament or cartilage repair and high-tibial osteotomies.[172] The procedure involves attaching the allograft to the tibia with bone plugs and then suturing the allograft to the capsule.

Some reports indicate that MR imaging may be helpful in determining the appropriate size of the meniscal transplant;[173] however, other studies suggest radiographs are nearly as accurate as MR.[174] MR imaging is helpful preoperatively to evaluate the integrity of the ligaments and cartilage.[169]

Articular Cartilage repair techniques

Bone Marrow Stimulation

Several techniques may be used to stimulate the growth of new fibrocartilage from bone marrow stem cells.

These techniques include abrasion, subchondral drilling, and microfracture.

Abrasion arthroplasty involves the removal of subchondral bone to a depth of 1–3 mm beneath the cartilage defect, a procedure that results in the formation of a fibrin clot.[175]

In the microfracture procedure, an awl or a pick is used to create multiple 4-mm-deep pits in the subchondral bone beneath the cartilage defect.[176, 177]

Subchondral drilling involves puncturing the subchondral bone by using a drill. Multipotential stem cells migrate from marrow beneath these pits to the cartilage defect.

Each of these techniques eventually leads to the formation of fibrocartilaginous repair tissue.

Microfracture remains the most commonly performed cartilage repair procedure. No absolute contraindications or unique risks to the microfracture technique have been established.[178] The best short-term results are observed in the presence of a good fill grade, a low patient body-mass index, and a short duration of preoperative symptoms.[179]

However, the new fibrocartilage has insufficient structural, biomechanical, and biochemical properties to sustain normal joint function over the long term.[178]

Tissue-based Cartilage Repair

Autologous Osteochondral Autograft Transplantation (Mosaicplasty)

In this procedure, osteochondral plugs are harvested from non– weight-bearing areas such as the lateral femoral condyle or the trochlea and transplanted in an articular defect in the same person.[180]

Osteochondral autograft transplantation or mosaicplasty provides autologous hyaline articular cartilage. This procedure is performed most frequently in the knee and ankle joints and is indicated for the repair of cartilage defects of 1–4 cm2, osteochondritis dissecans, and Osteonecrosis.[181]

Osteochondral autografts are less likely than allografts to evoke an immune response leading to graft rejection and are associated with a higher rate of graft incorporation.

However, autograft transplantation is limited by the availability of donor-graft tissue, the age dependence of donor cartilage, and the potential risk of donor site morbidity.(178)

Osteochondral Allograft Transplantation.

A fresh shell or plug of bone and cartilage harvested from a cadaver is transplanted to fill a full thickness chondral or osteochondral defect. The transplanted tissue provides the hyaline cartilage.

This type of graft is useful for repairing large defects, and there is no donor-site morbidity.(182) However, unlike the grafts used in most other cartilage repair techniques, fresh shell osteochondral allografts are associated with the risks of immunologic rejection and of disease transmission from donor to recipient.(178)

Cell-based Cartilage Repair

Autologous Chondrocyte Implantation

The classic procedure of autologous chondrocyte implantation, which was first described in the mid-1990s, traditionally consists of two stages. In the first stage, healthy chondrocytes harvested from a non–weight-bearing cartilaginous surface are cultured in vitro for 3–5 weeks.

In the second stage, approximately 1 month later, the cultured chondrocytes are implanted via an arthrotomy and covered with a periosteal flap, the edges of which are secured in place with fibrin glue or sutures. This technique may be used to treat cartilage defects of 2–12 cm2 in high-demand patients and osteochondritis dissecans lesions. If successful, it results in the formation of fibrocartilage that is similar to natural hyaline cartilage.(183)

However, autologous chondrocyte implantation may be complicated by graft hypertrophy, which usually has been observed within 6 months after the procedure. Most of the complications of autologous chrondrocyte implantation are directly related to the periosteal flap; revision arthroscopy rates of 4.8%–60% have been reported and attributed to problems with the periosteal flap, such as hypertrophy, delamination, and arthrofibrosis.(184)

There are many possible variations of the implantation procedure. In second-generation autologous chondrocyte implantation, a bilayer collagen membrane is used instead of a periosteal flap.(185)

In third-generation autologous chondrocyte implantation, a one-step arthrotomy (mini arthrotomy) is performed to allow the implantation of a 3D biologic scaffold optimized for the culture of seeded chondrocytes (matrix-associated autologous chondrocyte transplantation). The biologic scaffold material can be trimmed to fit a débrided cartilage ulcer and glued in place; no periosteal cover or sutures are needed. (186)

Fixation with Biodegradable Pins

Biodegradable pins made of polydioxanone may be used to stabilize osteochondral fractures, chondral flap tears, and osteochondritis dissecans lesions. These pins generally resorb within 6–24 months, with the resultant synthetic debris being cleared predominantly by macrophages.(178)