

MR Imaging–based Diagnosis and Classification of Meniscal Tears¹

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Abbreviations: ACL = anterior cruciate ligament, FSE = fast spin-echo, LM = lateral meniscus, MFL = meniscomfemoral ligament, MM = medial meniscus, PCL = posterior cruciate ligament, PD = proton density, PPV = positive predictive value, 3D = three-dimensional, 2D = two-dimensional

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Identify a meniscal tear on MR images.
- Describe and classify meniscal tears according to their various subtypes.
- Recognize normal meniscal anatomy and congenital variants to improve diagnostic accuracy.

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TEACHING POINTS

See last page

Magnetic resonance (MR) imaging is currently the modality of choice for detecting meniscal injuries and planning subsequent treatment. A thorough understanding of the imaging protocols, normal meniscal anatomy, surrounding anatomic structures, and anatomic variants and pitfalls is critical to ensure diagnostic accuracy and prevent unnecessary surgery. High-spatial-resolution imaging of the meniscus can be performed using fast spin-echo and three-dimensional MR imaging sequences. Normal anatomic structures that can mimic a tear include the meniscal ligament, meniscomfemoral ligaments, popliteomeniscal fascicles, and meniscomeniscal ligament. Anatomic variants and pitfalls that can mimic a tear include discoid meniscus, meniscal frounce, a meniscal ossicle, and chondrocalcinosis. When a meniscal tear is identified, accurate description and classification of the tear pattern can guide the referring clinician in patient education and surgical planning. For example, longitudinal tears are often amenable to repair, whereas horizontal and radial tears may require partial meniscectomy. Tear patterns include horizontal, longitudinal, radial, root, complex, displaced, and bucket-handle tears. Occasionally, meniscal tears can be difficult to detect at imaging; however, secondary indirect signs, such as a parameniscal cyst, meniscal extrusion, or linear subchondral bone marrow edema, should increase the radiologist's suspicion for an underlying tear. Awareness of common diagnostic errors can ensure accurate diagnosis of meniscal tears. *Online supplemental material is available for this article.*

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Introduction

Accurate and timely diagnosis of a meniscal tear is critical for reducing morbidity and planning treatment. It is well established that meniscal damage predisposes the adjacent articular cartilage to increased axial and shear stress, resulting in early degenerative osteoarthritis (1). The prevalence of asymptomatic tears, which typically are horizontal tears, increases with age (1,2). The incorporation of clinical information and the exclusion of an alternative cause can allow confident diagnosis of a symptomatic meniscal tear.

Since its introduction to clinical practice in the 1980s, magnetic resonance (MR) imaging has evolved into the preferred noninvasive imaging modality for evaluating internal knee derangements. With arthroscopy considered the standard of reference, MR imaging demonstrates high sensitivity (93% for the medial meniscus [MM] and 79% for the lateral meniscus [LM]) and specificity (88% for the MM and 96% for the LM) for detection of meniscal tears (3). However, despite advances in imaging, MR imaging continues to have inherent limitations, particularly for detection of small posterior horn tears and tears that involve less than one-third of the LM. In addition, a high false-positive rate has been reported for longitudinal tears of the MM posterior horn, possibly secondary to incomplete visualization of the far periphery of the MM at arthroscopy or to spontaneous healing (4,5).

The goal of this article is to review MR imaging parameters for detection of meniscal tears, normal meniscal anatomy, and anatomic variants and pitfalls and summarize criteria for MR imaging-based diagnosis and classification of various tear patterns. Diagnosis of the most common tear patterns seen at MR imaging will be described, including horizontal, longitudinal, radial, root, complex, displaced, and bucket-handle tears. An accurate and precise diagnosis can facilitate pre-surgical planning and prevent unnecessary surgical exploration or repeat surgery.

MR Imaging Parameters

The use of high-spatial-resolution MR imaging increases the ability to detect meniscal tears, particularly subtle nondisplaced tears (6). Spatial resolution can be improved by maximizing the matrix size while maintaining a small field of view and thin section thickness. However, these measures will result in a decrease in the signal-to-noise ratio, which can be partially compensated for by increasing the number of image acquisitions and by using dedicated high-performance extremity gradient coils. The typical parameters include a field of view of 16 cm or less, a matrix size of at least 192×256 (phase-encoding $\times$ frequency-encoding directions), and a section thickness of 3–4 mm (7). The accuracy of MR imaging for tear detection is comparable at field strengths ranging from 0.1–7.0 T; however, higher field strengths often improve spatial resolution and reader confidence and reduce image acquisition time (3,8).

When images from conventional spin-echo MR sequences are compared with those from optimized fast spin-echo (FSE) sequences with a short echo train length (less than five) and longer bandwidths, there is no statistically significant

difference in the tear detection rate (9). The major advantage of the FSE sequence is its faster imaging time, which decreases motion artifacts and allows more signal averages. More recently, three-dimensional (3D) sequences with isotropic resolution have been developed that provide thinner sections and reduce partial volume averaging. An additional advantage of isotropic 3D imaging is the ability to create multiplanar reformations in any plane after a single acquisition. Although the traditional two-dimensional (2D) FSE technique allows high in-plane spatial resolution, it acquires thick sections with inter-section gap, which prevents multiplanar reformation and requires separate acquisitions for each additional imaging plane, resulting in a longer overall scan time. To date, comparisons between 2D and 3D FSE techniques show relatively equivalent tear detection accuracy (10–12), with the exception of significantly lower sensitivity for detection of LM tears, particularly those involving the root, when 3D FSE imaging is used (13).

Historically, the use of proton-density (PD)-weighted sequences has been favored over T2-weighted sequences for detection of meniscal tears. It is postulated that the hydrogen nuclei within a tear are bound to macromolecules rather than being free, which gives them a shorter T2 relaxation time (14,15). However, for detection of MM root tears, coronal T2-weighted images show higher accuracy (96%, compared with 85% for PD-weighted images) (16). Therefore, when interpreting MR images of the knee, it is imperative to evaluate images from all of the sequences (17).

Normal Anatomy

Menisci

The menisci function to absorb shock, distribute axial load, assist in joint lubrication, and facilitate nutrient distribution (17). The MM and LM are wedge-shaped, semilunar, fibrocartilaginous structures. Each meniscus has a superior concave surface that conforms to the femoral condyle and a flat base that attaches to the tibia via the central root ligaments. This results in a thicker peripheral portion and a tapered central free edge. Circumferentially (longitudinally) oriented type I collagen bundles provide the meniscus with hoop strength and are critical to resisting axial load and preventing meniscal extrusion. Thinner radial fibers are interposed perpendicular to these bundles and act to tie the bundles together, forming a lattice and providing structural support for the menisci (17,18) (Fig 1a).

Each meniscus can be subdivided into the anterior horn, body, posterior horn, and roots (Fig

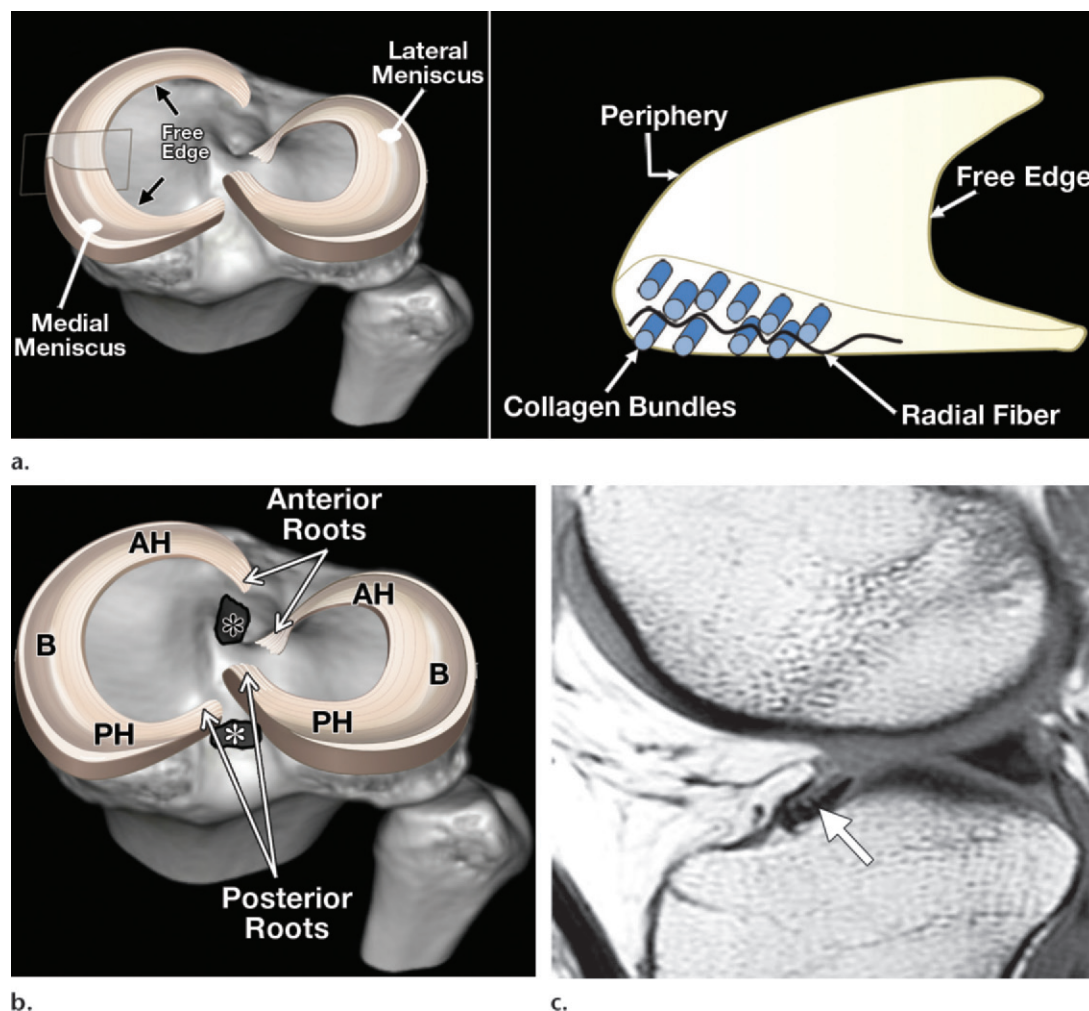


Figure 1. Normal meniscal anatomy. **(a)** Three-dimensional model (left) and cross-sectional diagram (right) of the semilunar meniscus highlight the concave surface, which conforms to the morphology of the femoral condyles. The result is increased contact area and a tapered central free edge. Circumferentially oriented collagen bundles (blue cylinders) provide hoop strength and course parallel to the long axis of the meniscus, while radial fibers form a lattice and provide additional structural support. **(b)** Three-dimensional model shows the meniscus subdivided into thirds (the anterior horn [AH], body [B], and posterior horn [PH]) and attached to the tibia via the anterior and posterior root ligaments. Note the proximity of the roots to the tibial attachment sites for the anterior cruciate ligament (ACL) (black *) and posterior cruciate ligament (PCL) (white *). **(c)** Sagittal PD-weighted MR image shows the striated appearance of the anterior horn of the LM (arrow) due to contributing insertional fibers that originate from the ACL.

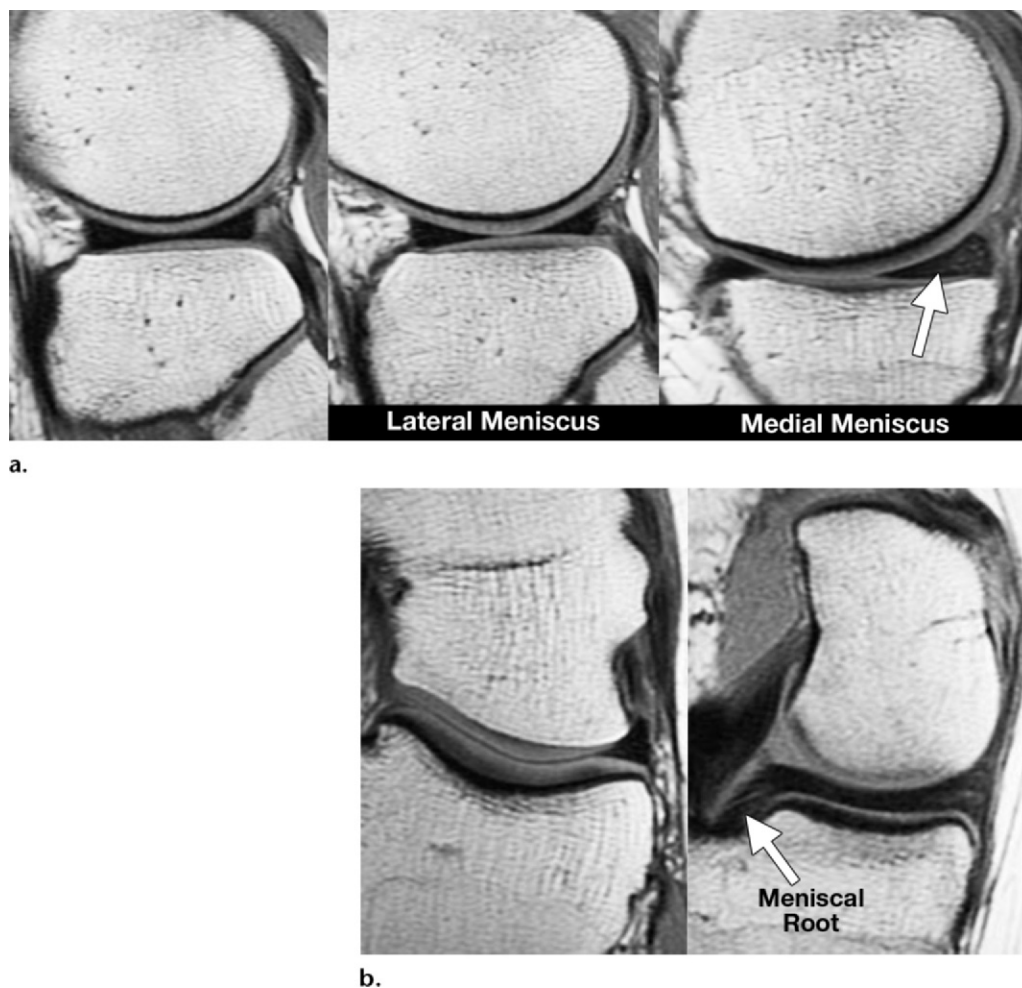
1b). The anterior and posterior roots typically attach to the central tibial plateau, serving as anchors and maintaining the normal meniscal position and biomechanical function. The intimate association between the anterior root of the LM and the ACL insertion site commonly results in a striated or comb-like appearance at MR imaging (Fig 1c) (19). In 2% of the population, an anomalous insertion of the MM parallels the ACL and can be mistaken for a tear (20). In addition, the MM anterior root can occasionally insert along the anterior margin of the tibia and mimic pathologic subluxation.

At MR imaging, the menisci appear as low-signal-intensity structures. Specifically, on sagittal

images, the menisci appear as either a “bow-tie” structure peripherally or opposing triangles centrally. On coronal images, the menisci appear either triangular or wedge-shaped, depending on whether the imaging plane is through the body or horn, respectively. Although the menisci have a similar composition and signal intensity, they are distinct. The MM is less mobile because of its peripheral attachments to the deep fibers of the medial collateral ligament. In addition, the MM has a more open C-shaped configuration and increases in width from anterior to posterior (Fig 2).

In newborns, the peripheral 50% of the meniscus is vascularized (the “red zone”) by the perimeniscal capillary plexus. The degree of vascular

Figure 2. Normal MR imaging appearance of the menisci. **(a)** Sagittal PD-weighted MR images show the typical bow-tie configuration of the meniscal body (left) and the opposing triangles of the horns (center and right). The posterior horn of the MM (arrow) is larger than the anterior horn, whereas the horns of the LM are similar in size and shape. **(b)** Coronal PD-weighted MR images demonstrate the triangular morphology of the meniscal body (left) and the elongated wedge shape of the posterior horn (right), which is continuous with the crescentic posterior meniscal root.



penetration declines with age, to about 10%–30% in adults. This vascular distribution is implicated in the spontaneous healing of peripheral tears and the increased intrameniscal signal intensity seen at imaging of children (17).

Surrounding Anatomy

Common anatomic structures that can mimic a tear include the transverse meniscal ligament, meniscofemoral ligaments (MFLs), popliteomeniscal fascicles, and meniscomeniscal ligament.

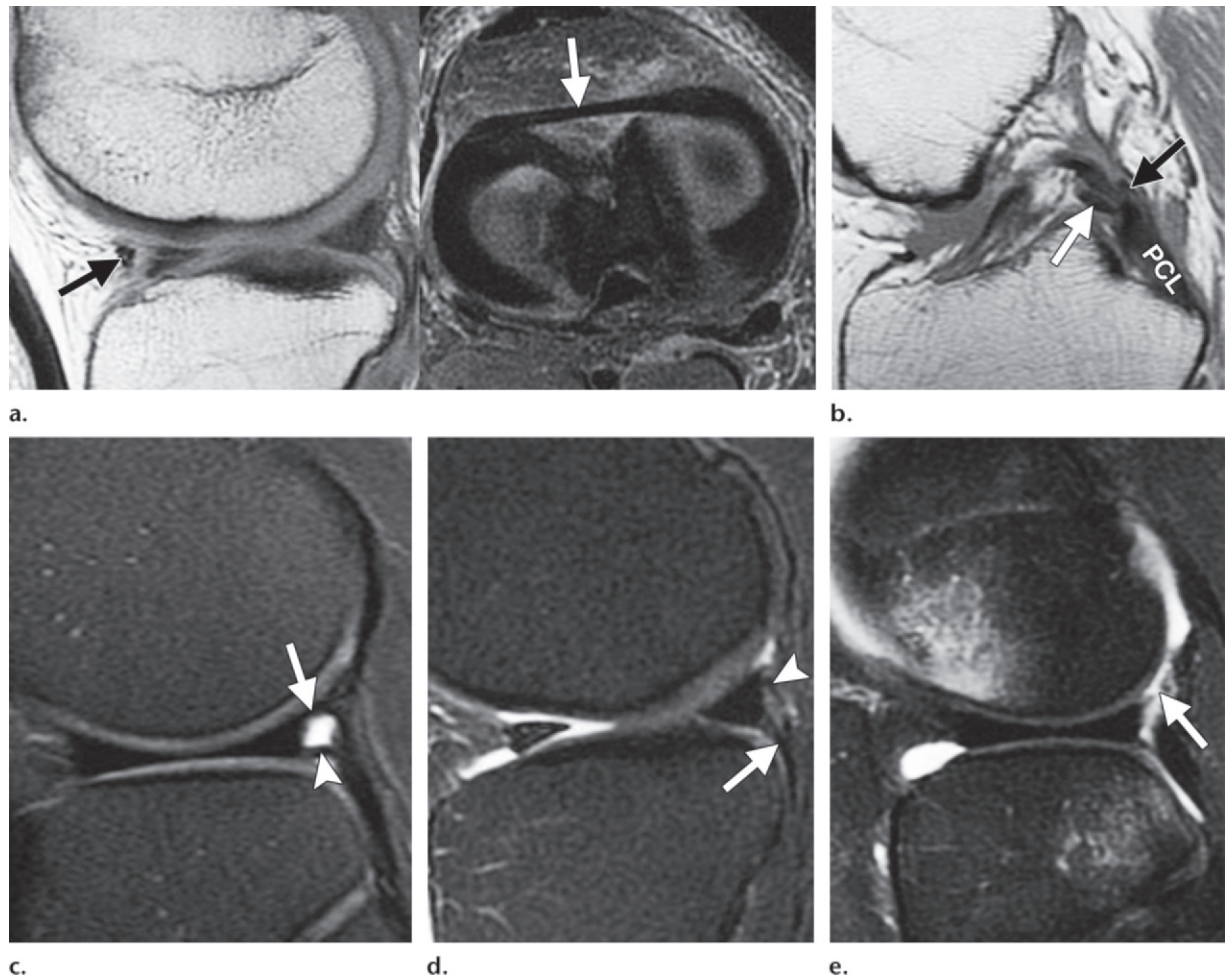
The transverse meniscal (geniculate) ligament is a thin fibrous band that is present in 90% of dissection specimens and 83% of MR imaging studies. It connects and stabilizes the anterior horns of the menisci (21). On sagittal images, this ligament can simulate an anterior root tear (Fig 3a).

The MFLs originate from the posterior horn of the LM and insert onto the lateral aspect of the medial femoral condyle. At least one MFL

is identified in 89% of dissection specimens and 93% of MR imaging studies (22). The MFLs assist the PCL and help control the mobility of the posterior horn of the LM during knee flexion and extension (23). The commonly recognized MFL ligaments are the Humphry and Wrisberg ligaments, which travel anterior and posterior to the PCL, respectively (Fig 3b). Recently, studies have reported that a far lateral insertion of the MFL onto the posterior horn of the LM (seen on four or more 3-mm-thick images with a 0.5-mm intersection gap) should be considered a probable peripheral longitudinal tear (24).

The popliteomeniscal fascicles are synovial-lined fibrous bands that attach to the LM posterior horn and help form the popliteal hiatus. They stabilize the posterior horn and help control its motion (25). At MR imaging with fluid-sensitive sequences, the anteroinferior and posterosuperior fascicles are visualized in ap-

Figure 3. Surrounding anatomy. **(a)** Sagittal PD-weighted MR image (left) shows an apparent anterior root tear (black arrow), which, when followed on multiple imaging sections and better depicted on the axial fluid-sensitive reconstructed MR image (right), is shown to be the normal transverse meniscal ligament (white arrow). **(b)** Sagittal PD-weighted MR image shows the Humphry (white arrow) and Wrisberg (black arrow) ligaments, which are located anterior and posterior to the PCL, respectively. **(c)** Sagittal T2-weighted MR image shows the posterosuperior (arrow) and anteroinferior (arrowhead) fascicles, which form the roof and floor of the popliteal hiatus, respectively. **(d)** Sagittal T2-weighted MR image obtained at a more medial level than **c** depicts the posteroinferior fascicle (arrow). Note the adjacent MFL (arrowhead). **(e)** Sagittal T2-weighted MR image shows a torn posterosuperior fascicle (arrow), which was found to be associated with an arthroscopically proved peripheral longitudinal LM tear. Note the “kissing” bone contusions from an ACL tear.



proximately 90% of asymptomatic knees (Fig 3c) (26). In cadaveric studies, a posteroinferior fascicle can occasionally be identified (Fig 3d) (27). These fascicles can mimic a peripheral posterior horn flap tear. **A tear of the posterosuperior fascicle is highly associated with, but not specific for, a tear of the LM, with a sensitivity, specificity, and positive predictive value (PPV) of 89%, 96%, and 79%, respectively (28) (Fig 3e).**

The oblique meniscomeniscal ligament connects the anterior horn of one meniscus with the posterior horn of the contralateral meniscus and is present in only 1%–4% of knees (29). When present, it can simulate a centrally displaced meniscal fragment.

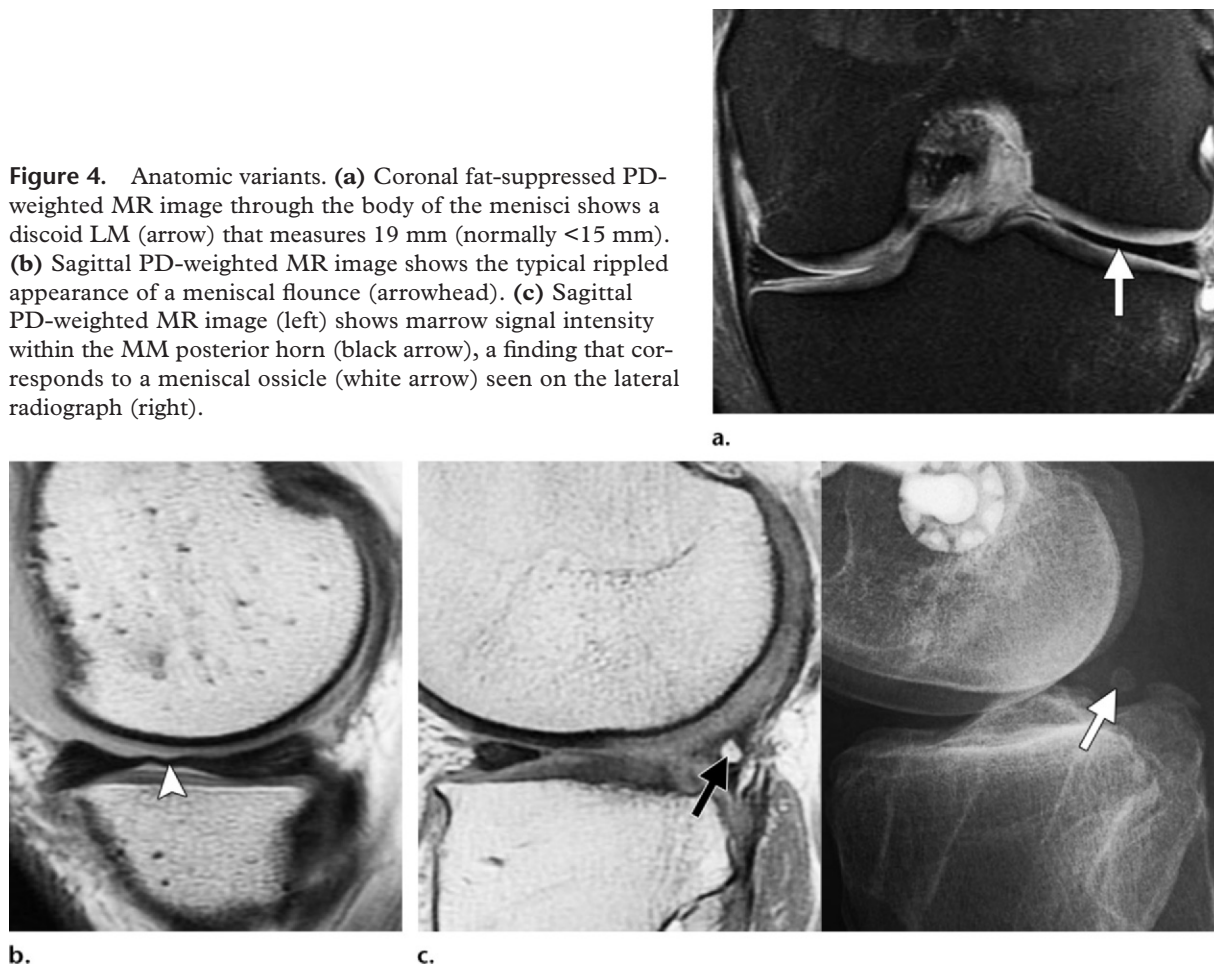
Anatomic Variants and Pitfalls

Anatomic variants and pitfalls that can mimic a tear include discoid meniscus, meniscal flocule, a meniscal ossicle, and chondrocalcinosis.

Discoid Meniscus

Discoid meniscus represents an enlarged meniscus with further central extension onto the tibial articular surface. It is seen in 1%–5% of knees and is 10–20 times more common in the LM than in the MM (30). The Watanabe classification recognizes three distinct variants of discoid meniscus: (a) the complete variant has a block-shaped meniscus that covers the entire tibial plateau; (b) the partial variant has a meniscus that covers 80% or less of the tibial plateau; and (c) the

Figure 4. Anatomic variants. **(a)** Coronal fat-suppressed PD-weighted MR image through the body of the menisci shows a discoid LM (arrow) that measures 19 mm (normally <15 mm). **(b)** Sagittal PD-weighted MR image shows the typical rippled appearance of a meniscal flounce (arrowhead). **(c)** Sagittal PD-weighted MR image (left) shows marrow signal intensity within the MM posterior horn (black arrow), a finding that corresponds to a meniscal ossicle (white arrow) seen on the lateral radiograph (right).



Wrisberg variant has a thickened posterior horn, lacks the normal posterior meniscal attachments, and can cause snapping knee syndrome (31). The modified Watanabe classification includes a ring-shaped meniscus with connection between the roots. This variant can mimic a medially displaced meniscal fragment; however, no donor site can be identified at imaging (32). Discoid meniscus is diagnosed when the body of the meniscus measures 15 mm or more on a midline coronal image (Fig 4a) or when three or more bow-tie shapes are identified on contiguous sagittal (4-mm-thick) images (33).

Discoid menisci are often incidentally detected, with treatment reserved for symptomatic patients suspected of having a tear. Tears are more common with the complete discoid meniscus variant and often display horizontal or longitudinal tear patterns (32). MR imaging has widely variable sensitivity and specificity for detection of tears within a discoid meniscus because of the increased meniscal vascularity and diffuse intrameniscal signal intensity (34,35). Therefore, diagnosis of a tear relies more heavily on morphologic distortion than on abnormal signal intensity. However, an area of linear in-

creased signal intensity that is seen to unequivocally contact the articular surface on two or more images is almost always associated with a meniscal tear. In contrast, diffuse intrameniscal signal intensity extending to the articular surface has been shown to have a poor PPV (57%–78%) (36,37). Currently we report the latter finding as a possible tear.

Meniscal Flounce

Meniscal flounce is a rippled appearance of the free nonanchored inner edge of the MM, which can be seen in 0.2%–0.3% of asymptomatic knees (Fig 4b). Typically, this is secondary to flexion of the knee and redundancy of the free edge of the MM. This distortion does not indicate a tear; however, on coronal images, it may simulate a truncated meniscus and mimic a radial tear. At arthroscopy, the “flounce” sign is more common because of knee positioning and anesthetic relaxation and usually signifies the absence of a tear (38).

Meniscal Ossicle

A meniscal ossicle is a rare entity with a predilection for the posterior horn of the MM. Its cause

may be developmental, degenerative, or post-traumatic (39,40). On radiographs, the ossicle can be mistaken for a loose body, while at MR imaging, its increased signal intensity can mimic a tear (Fig 4c). A review of the patient's radiographs can prevent false-positive diagnosis of a tear. Symptoms result from mass effect or from an associated tear, which can be treated with arthroscopic resection.

Chondrocalcinosis

Similar to a meniscal ossicle, chondrocalcinosis can result in increased meniscal signal intensity, thereby lowering the sensitivity and specificity of MR imaging for detection of tears (78%–89% sensitivity and 72%–79% specificity in patients with chondrocalcinosis, compared with 93%–100% sensitivity and 100% specificity in those without) (41). Its prevalence increases with age and ranges from 5% to 15%. Once again, correlation with radiographs will aid in reducing the number of false-positive diagnoses.

MR Imaging–based Diagnosis of Meniscal Tears

The prevalence of meniscal tears increases with age, and meniscal tears are often associated with and contribute to degenerative joint disease. Tears are more common in the posterior horn of the menisci, particularly favoring the more constrained MM. However, in younger patients with an acute injury, LM tears are more common. Isolated tears in the anterior horn are uncommon, accounting for 2% and 16% of MM and LM tears, respectively (42). In the presence of ACL tears, there is an increased prevalence of peripheral tears and a decreased sensitivity for detection of LM tears at MR imaging (69% sensitivity, compared with 94% sensitivity in patients without ACL tears). Therefore, special attention should be directed to this location, where a subtle peripheral tear may be present (43).

MR imaging is a proved, highly accurate modality for detection of meniscal injuries, with excellent arthroscopic correlation (44). Normal menisci should have low signal intensity at MR imaging; however, globular or linear increased intrameniscal signal intensity can be seen in children (due to normal vascularity), in adults with internal mucinous degeneration, and after trauma due to acute contusion. **MR imaging criteria for diagnosing a tear include meniscal distortion in the absence of prior surgery or increased intrasubstance signal intensity unequivocally contacting the articular surface. If these criteria are seen on two or more images, fulfilling the “two-slice-touch” rule, then the PPV for a tear is 94% in the MM and 96% in the LM, and the**

imaging findings should be reported as a meniscal tear. The findings must be identified in the same area on any two consecutive MR images, which can be two coronal images, two sagittal images, or one coronal and one sagittal image. If these criteria are present on only one image, then the PPV for a tear is 43% in the MM and 18% in the LM, and the finding is best reported as a possible tear (42,45). This latter description gives the referring clinician flexibility in managing these cases. In contrast, increased intrasubstance signal intensity without extension to the articular surface is often not associated with a tear at surgery (46), nor has this finding been shown to progress to a tear (47).

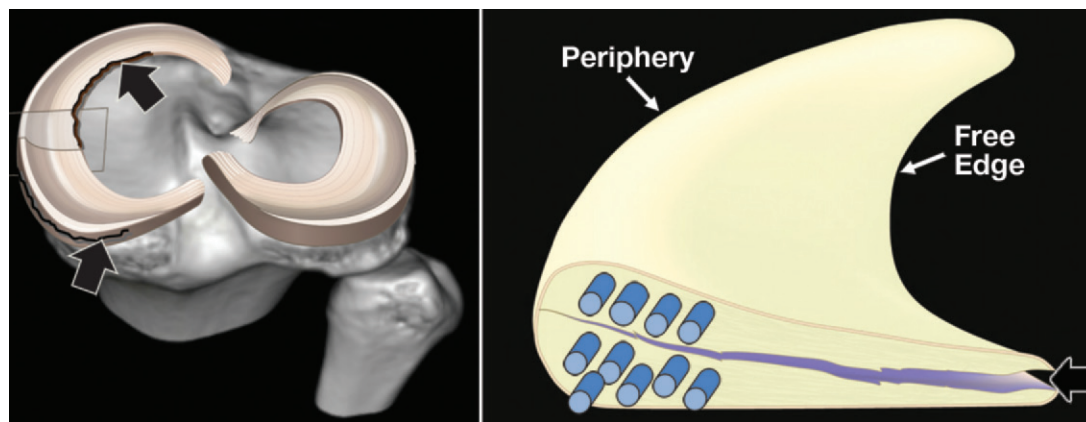
Although most tears can be confidently diagnosed on sagittal images, coronal images are important for confirming and accurately characterizing various tear patterns. Small radial tears, horizontal tears of the body, and bucket-handle tears may be difficult to reliably detect on sagittal images because of volume averaging; these tears may be better depicted on coronal images (48). In addition, axial images may be helpful for detection of small radial tears, displaced tears, and peripheral tears of the LM posterior horn (49).

Meniscal Tear Classification

Meniscal tears can be treated with conservative therapy, surgical repair, or partial or complete meniscectomy. Longitudinal tears are often amenable to repair, whereas horizontal and radial tears may require partial meniscectomy (50,51). Hence, when a tear is identified, accurate description of its morphology and tear pattern is critical for treatment planning. Currently, there is no standard tear classification system. The most common tear patterns described are horizontal, longitudinal, radial, root, complex, displaced, and bucket-handle tears.

Horizontal Tear

A horizontal tear runs parallel to the tibial plateau, involves either one of the articular surfaces or the central free edge, and extends toward the periphery, dividing the meniscus into superior and inferior halves (Fig 5). These tears usually occur in patients older than 40 years without an inciting trauma and are more common in the setting of underlying degenerative joint disease (52). The typical MR imaging appearance is a horizontally oriented line of high signal intensity that contacts the meniscal surface or free edge (Fig 6). Parameniscal cyst formation is associated with complete horizontal tears that extend to the periphery, presumably secondary to direct communication with the joint fluid (Fig 6b) (53). Treatment often involves débridement of the smaller unstable



a.

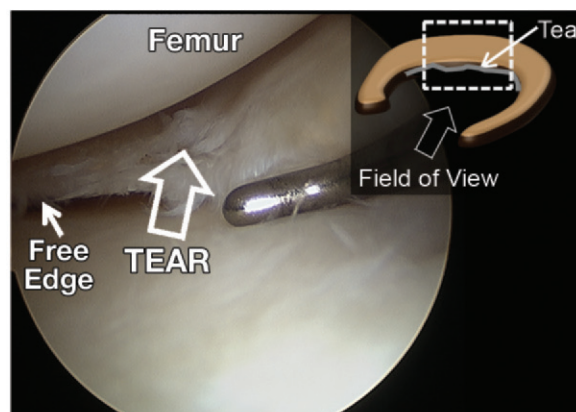
Figure 5. Horizontal tear. **(a)** Three-dimensional model (left) and cross-sectional diagram (right) show a horizontal tear (black arrows) that courses between the longitudinal collagen bundles (blue cylinders) without disrupting them and separates the meniscus into upper and lower halves. **(b)** Image from arthroscopic video shows a typical horizontal tear that extends into the free edge. Inset shows the arthroscopic field of view.

meniscal leaf and decompression of the associated parameniscal cyst. Partial meniscectomy with open cystectomy has been shown to result in improved surgical outcomes compared with partial meniscectomy alone in this circumstance (54).

Longitudinal Tear

Longitudinal tears run perpendicular to the tibial plateau and parallel to the long axis of the meniscus and divide the meniscus into central and peripheral halves (Fig 7, Movie 1) (52). Unlike horizontal or radial tears, pure longitudinal tears do not involve the free edge of the meniscus. These tears often occur in younger patients after significant knee trauma (55) and have a propensity to involve the peripheral third of the meniscus and posterior horns (15). The typical MR imaging appearance is a vertically oriented line of high signal intensity that contacts one or both articular surfaces (Fig 8).

There is a close association between peripheral longitudinal tears and ACL tears. Specifically, 90% of MM and 83% of LM peripheral longitudinal tears have an associated ACL tear (43). Peripheral longitudinal tears of the LM posterior horn are often difficult to identify because of the surrounding complex anatomy and posterior attachments. As discussed in the anatomy section, disruption of the posteriosuperior popliteomeniscal fascicle has a high PPV for tears of the LM posterior horn (Fig 3e), and a far lateral attachment of the MFL (>14 mm beyond the lateral border of the PCL) also



b.

likely represents a tear. In our experience, identifying peripheral longitudinal tears of the posterior horn of the LM can be difficult because of the complex posterior attachments of the meniscus. In this circumstance, the tear may be more conspicuous on sagittal T2-weighted MR images.

Radial Tear

A radial tear runs perpendicular to both the tibial plateau and the long axis of the meniscus and transects the longitudinal collagen bundles as it extends from the free edge toward the periphery (Fig 9, Movie 2). In contrast to horizontal and longitudinal tears, radial tears disrupt the meniscal hoop strength, resulting in a dramatic loss of function and possible meniscal extrusion. The tears are frequently not repaired because they are located within the avascular “white zone” and therefore have a low likelihood of healing or regaining significant function. Detection of small radial tears can be difficult, which often results in their underdiagnosis before surgery (43,56).

Radial tears commonly involve the posterior horn of the MM or the junction of the anterior horn and body of the LM. On axial MR images, these tears appear as clefts oriented perpendicular to the free edge. Various imaging signs can be

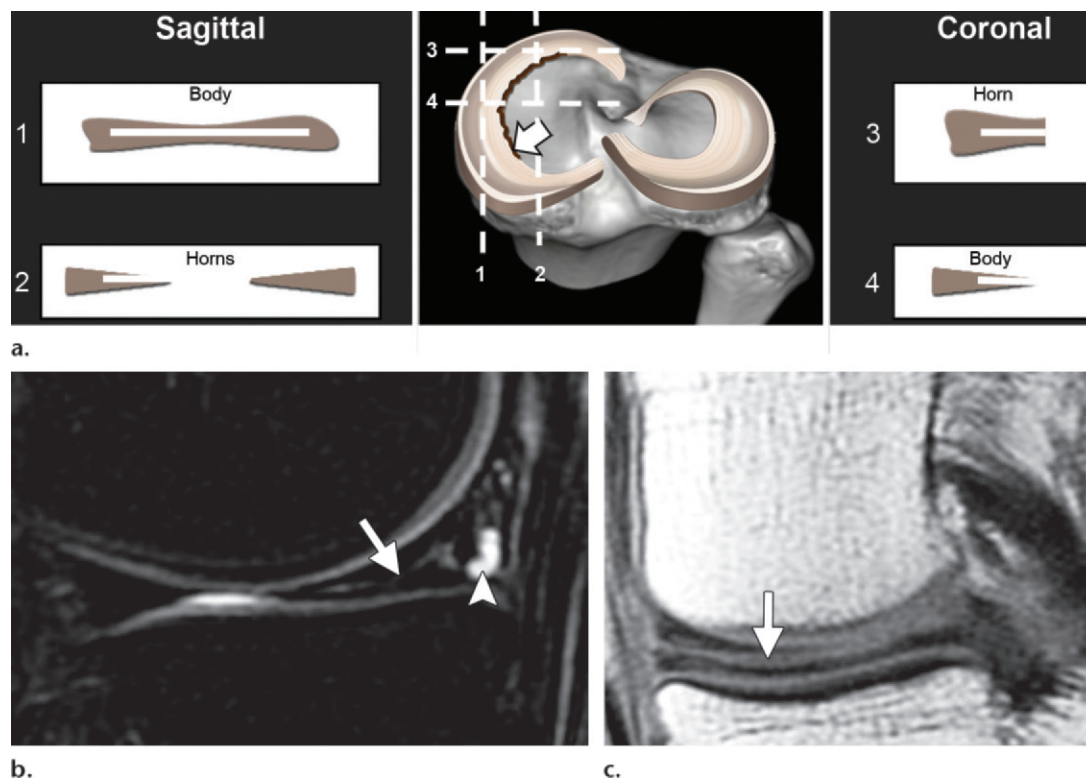


Figure 6. Expected MR imaging appearance of a horizontal tear. **(a)** Three-dimensional model (center) shows a horizontal tear (arrow), and diagrams show the expected appearance of the tear on sagittal (left) and coronal (right) MR images. Dashed lines = orientation of imaging planes. **(b)** Sagittal T2-weighted MR image shows a tear of the posterior horn (arrow) and an associated multiloculated parameniscal cyst (arrowhead). **(c)** Coronal PD-weighted MR image shows a horizontal tear of the meniscal body (arrow) that contacts the superior articular surface.

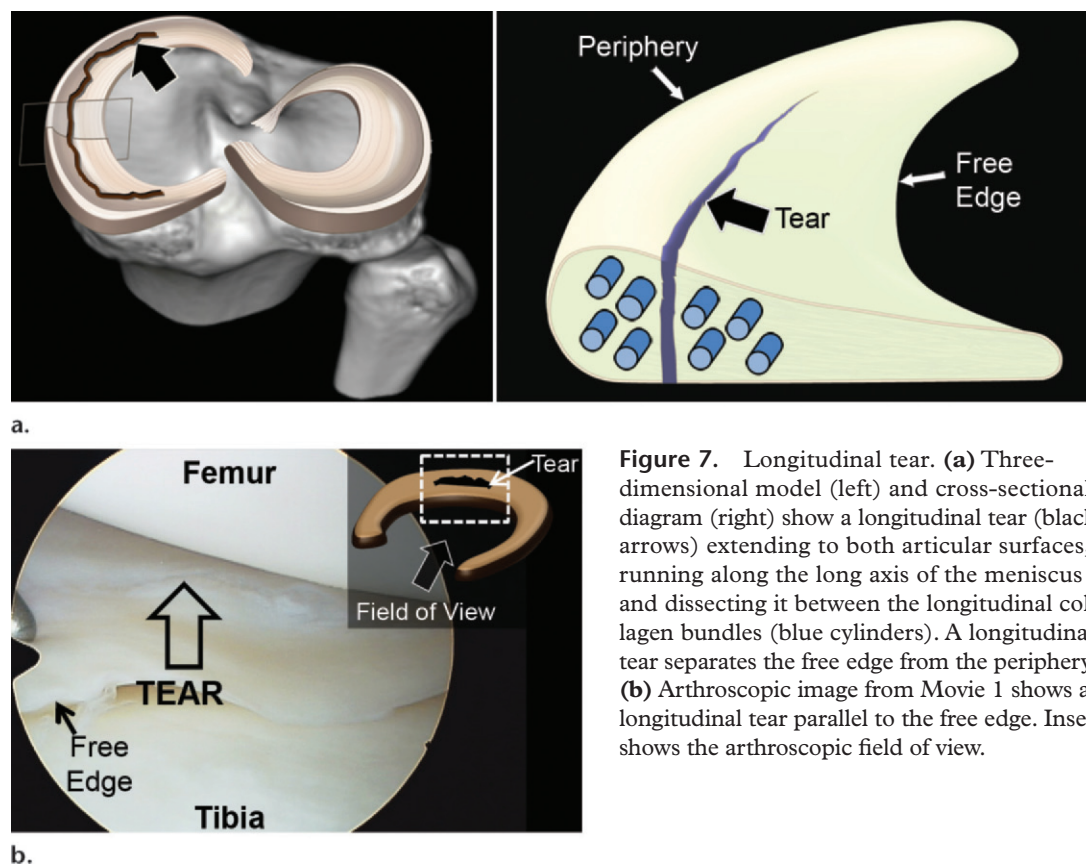


Figure 7. Longitudinal tear. **(a)** Three-dimensional model (left) and cross-sectional diagram (right) show a longitudinal tear (black arrows) extending to both articular surfaces, running along the long axis of the meniscus and dissecting it between the longitudinal collagen bundles (blue cylinders). A longitudinal tear separates the free edge from the periphery. **(b)** Arthroscopic image from Movie 1 shows a longitudinal tear parallel to the free edge. Inset shows the arthroscopic field of view.

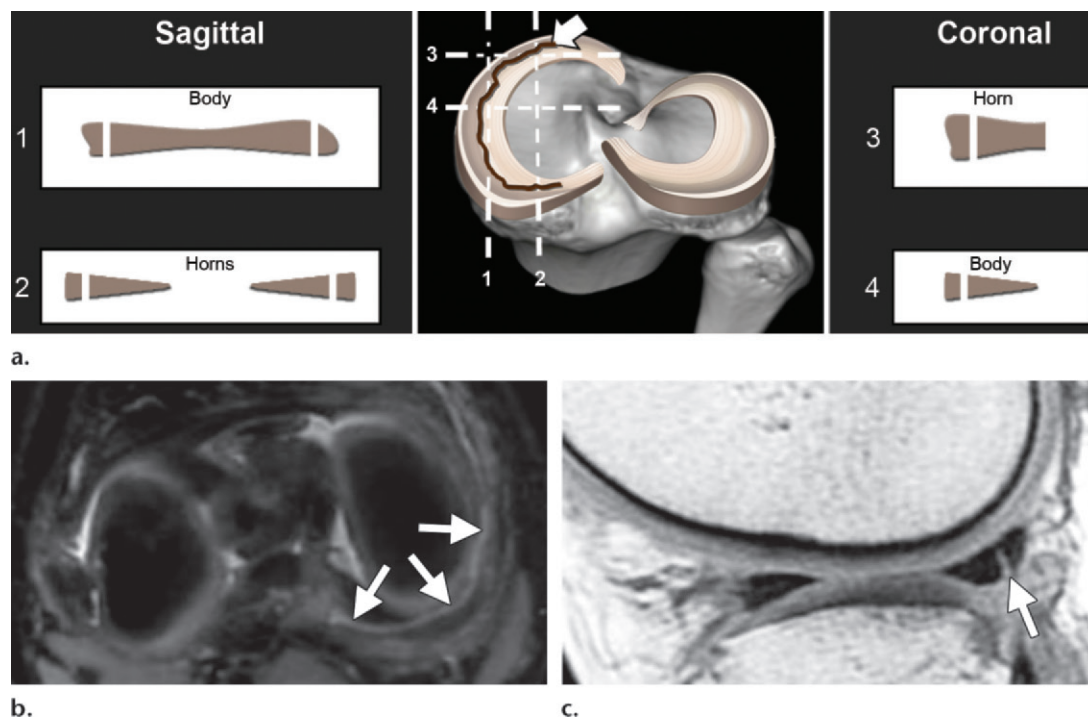


Figure 8. Expected MR imaging appearance of a longitudinal tear. **(a)** Three-dimensional model (center) shows a typical longitudinal tear (arrow) that divides the meniscus into inner and outer halves, and diagrams show the expected appearance of the tear on sagittal (left) and coronal (right) MR images. Dashed lines = orientation of imaging planes. **(b)** Axial fluid-sensitive reformatted MR image shows a peripheral longitudinal tear involving the posterior body and posterior horn that extends into the posterior root (arrows). **(c)** Sagittal PD-weighted MR image shows a peripheral longitudinal tear with increased intrasubstance signal intensity that unequivocally contacts the articular surface in a vertical orientation (arrow). This type of tear should not extend to the free edge.

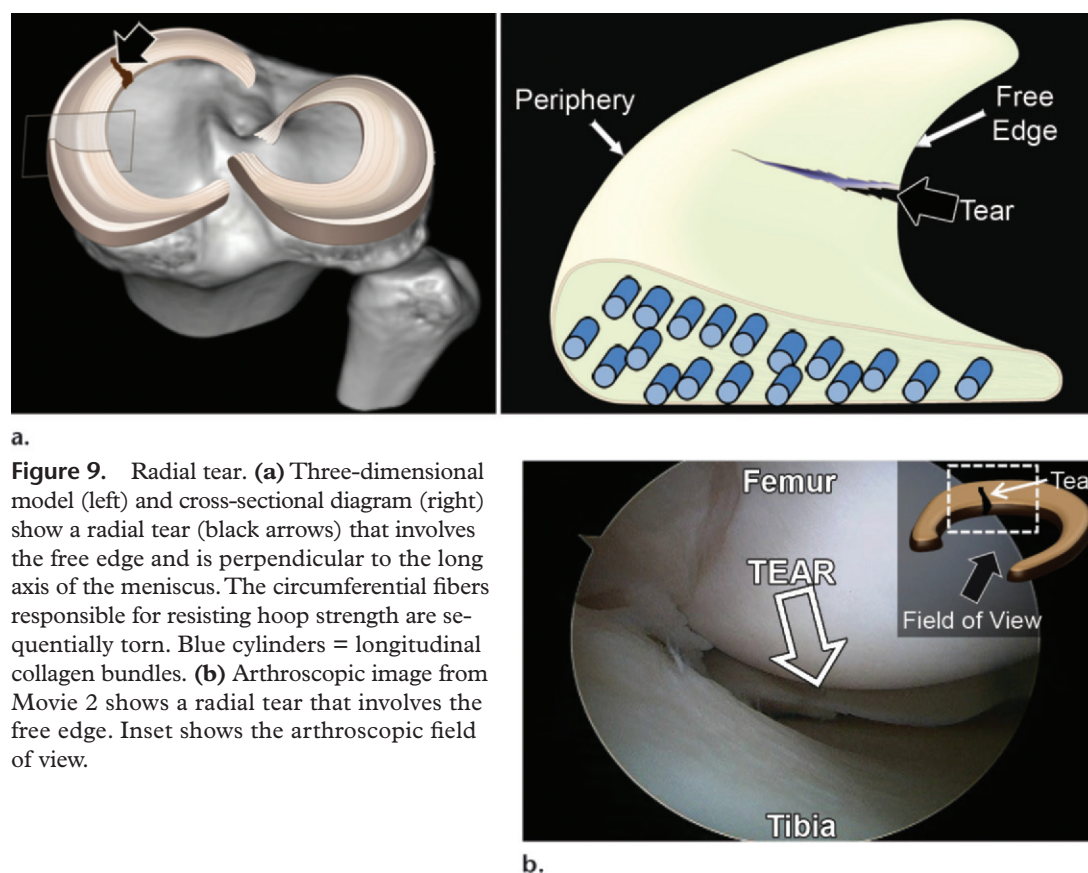


Figure 9. Radial tear. **(a)** Three-dimensional model (left) and cross-sectional diagram (right) show a radial tear (black arrows) that involves the free edge and is perpendicular to the long axis of the meniscus. The circumferential fibers responsible for resisting hoop strength are sequentially torn. Blue cylinders = longitudinal collagen bundles. **(b)** Arthroscopic image from Movie 2 shows a radial tear that involves the free edge. Inset shows the arthroscopic field of view.

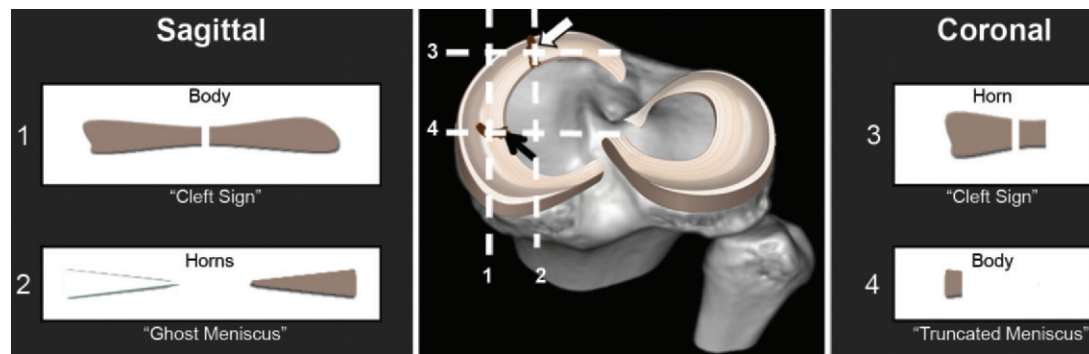


Figure 10. Expected MR imaging appearance of a radial tear. Three-dimensional model (center) shows two radial tears: a partial-thickness tear of the body (black arrow) and a full-thickness tear of the anterior horn (white arrow). Dashed lines = orientation of imaging planes. Diagrams on the left and right show the expected MR imaging appearance of a radial tear, which varies depending on whether the imaging sequence is performed orthogonal (1 and 3) or in plane (2 and 4) to the orientation of the tear. If the image is obtained perpendicular to the tear (1 and 3), a cleft will be identified; however, if the image is obtained parallel to the tear (2 and 4), the meniscus will appear truncated or absent. Radial tears involve the free edge of the meniscus, which distinguishes them from longitudinal tears.

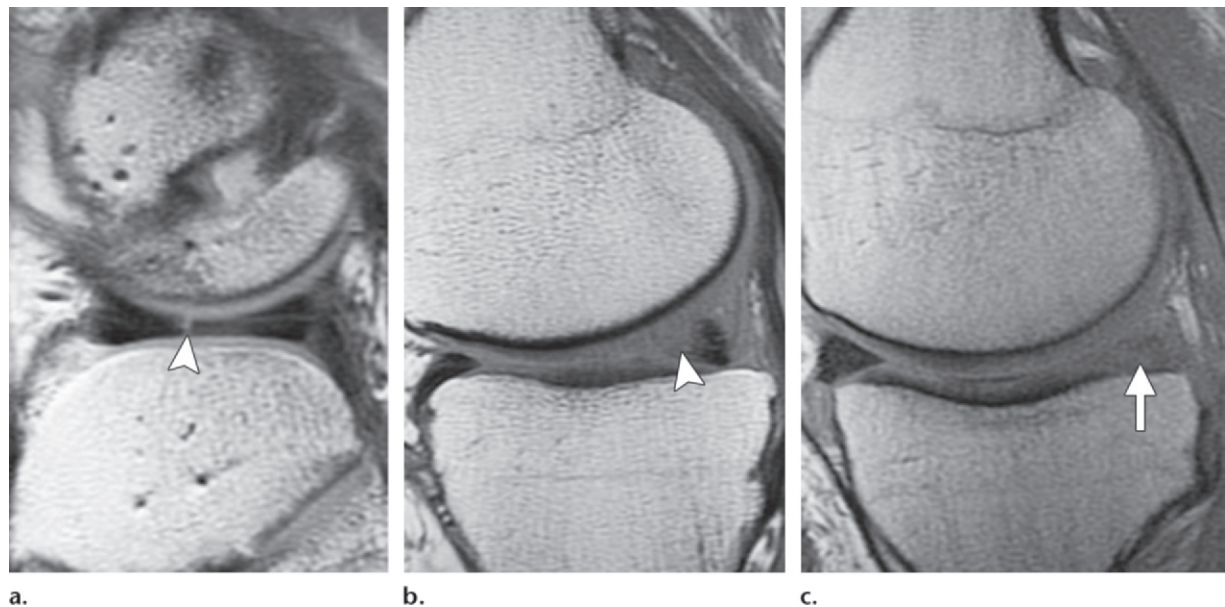


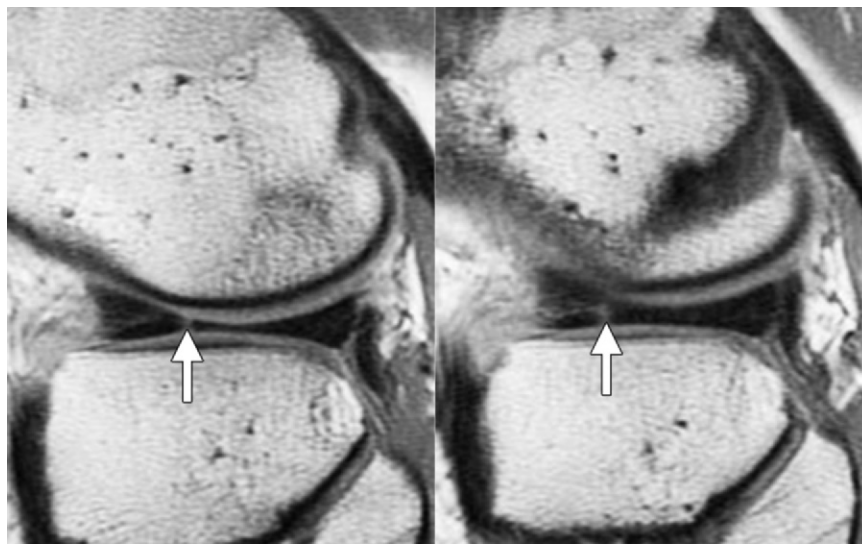
Figure 11. MR imaging signs of a radial tear. Sagittal PD-weighted MR images demonstrate the cleft sign (arrowhead in **a**), the truncated triangle sign of a partial-thickness tear (arrowhead in **b**), and the ghost meniscus sign associated with a full-thickness tear (arrow in **c**). Each tear involves the free edge of the meniscus.

seen with a radial tear, including the “truncated triangle,” “cleft,” “marching cleft,” and “ghost meniscus” signs. These variable appearances depend on the tear location relative to the imaging plane (Fig 10). For example, a tear through the meniscal body would appear as a cleft on sagittal MR images (Fig 11a) and as a truncated or ghost meniscus on coronal MR images. Conversely, a tear through the horn would appear as a truncated or ghost meniscus on sagittal MR images (Fig 11b, 11c) and as a cleft on coronal MR images. Typically, a truncated meniscus represents truncation of the free edge, with preservation of its peripheral portion, often as a result of a

partial-thickness tear. In contrast, a ghost meniscus has no in-plane residual normal meniscus, often as a result of a full-thickness tear. If a tear is located at the junction of the horn and body (obliquely oriented relative to both coronal and sagittal planes), it would appear as a “marching cleft” that progresses away from the free edge on contiguous MR imaging sections (Fig 12). Identification of these MR imaging signs can improve the detection rate of radial tears to 89% (50,57).

The cleft sign is not specific and can be seen with both longitudinal and radial tears, depending on the location of the tear relative to the imaging plane (Fig 13). On coronal MR images,

Figure 12. Marching cleft sign of a radial tear. **(a)** Sagittal PD-weighted contiguous MR images show a vertically oriented cleft (arrows) “marching” from the free edge into the substance of the meniscus at the junction of the body and anterior horn. **(b)** Axial fluid-sensitive reconstructed MR image shows the oblique course of a radial tear (arrow) with respect to the sagittal plane, which accounts for the MR imaging appearance of a tear propagating out of plane.



a.

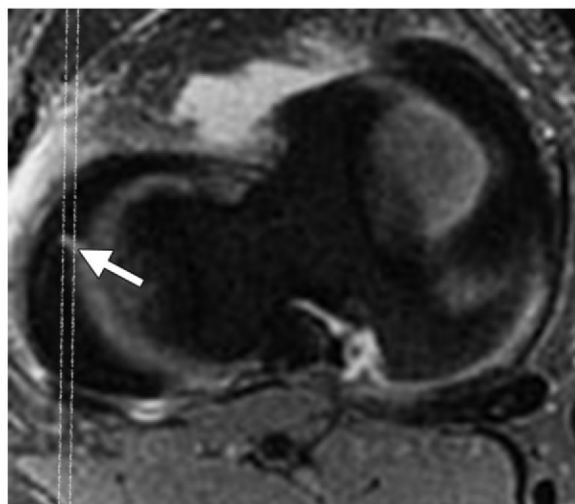
if the cleft is within the body, it is the result of a longitudinal tear. If the cleft is within the horn, it is the result of a radial tear. The opposite combination holds true on sagittal MR images.

Root Tear

A root tear is typically a radial-type tear (Fig 14, Movie 3). Complete root tears have a high association with meniscal extrusion, particularly when the tear occurs in the MM (58,59). Root tears have received increased recognition in recent years, partially because of their previous underdiagnosis at both MR imaging and arthroscopy. However, if attention is directed to the roots, the sensitivity and specificity for tear detection at MR imaging increase to 86%–90% and 94%–95%, respectively (16,60). Coronal fluid-sensitive MR imaging sequences allow better definition of the roots, which partially compensates for magic-angle and pulsation artifacts. On coronal MR images, the root should course over its respective tibial plateau on at least one image (Fig 2b). On sagittal MR images, if the posterior root of the MM is not detected just medial to the PCL, a root tear should be suspected. In addition, when an ACL tear is present, there is an increased incidence of lateral root tears (58,60). Acute root tears without significant underlying degenerative changes are often promptly repaired because the surrounding rich synovial blood supply facilitates postoperative healing (61,62).

Complex Tear

A complex tear includes a combination of radial, horizontal, and longitudinal components (any two or all three) (Fig 15). Often the meniscus appears fragmented, with the tear extending in more than one plane.



b.

Displaced Tear

Displaced tears include free fragments, displaced flap tears, and bucket-handle tears. These tears often manifest with mechanical obstruction and require surgical reattachment or débridement (Movie 4). Small free fragments and flaps can be missed at arthroscopy. Therefore, identification of these fragments before surgery is imperative, as retention of a meniscal flap often results in persistent pain and potential knee locking. Awareness of the typical displacement patterns can be instrumental. Flap tears occur six to seven times more frequently in the MM, where in two-thirds of cases, fragments are displaced posteriorly (near or posterior to the PCL); in the remaining cases, fragments course into either the intercondylar notch or superior recess (Fig 16a) (63). In the LM, fragments are equally distributed along the posterior joint line and lateral recess (Fig 16b, 16c) (64). In the absence of prior surgery, a radial-type tear, or severe underlying chondrosis, a foreshortened

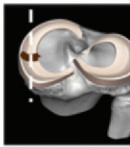
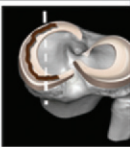
Location	Coronal Plane		Sagittal Plane	
Body	Longitudinal Tear		Radial Tear	
	Radial Tear		Longitudinal Tear	

Figure 13. Cleft sign of longitudinal and radial tears. Three-dimensional models show tears (brown outlines) and the orientation of the imaging planes (dashed white lines). If the imaging plane is perpendicular to the course of the tear, the tear will appear as a vertically oriented cleft through the meniscus. Radial tears, however, extend to and involve the free edge.

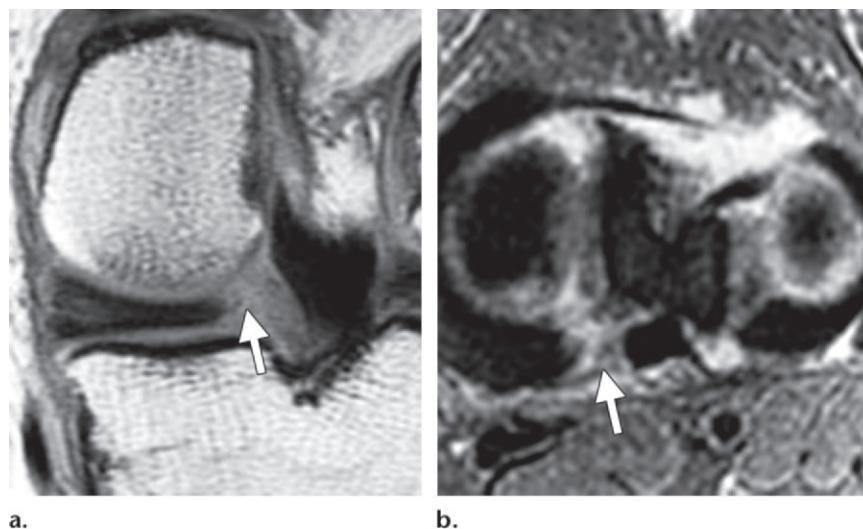
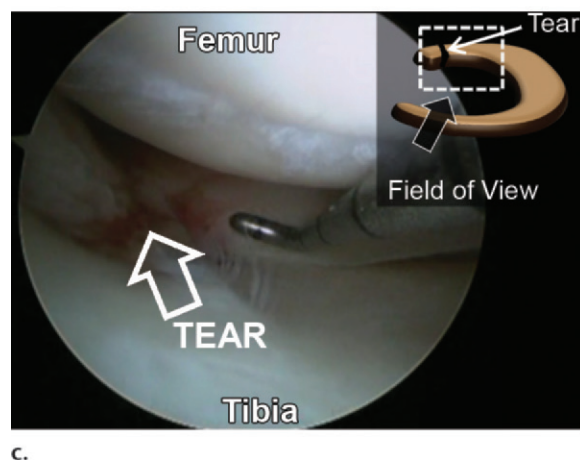


Figure 14. Complete root tear. (a, b) Coronal PD-weighted (a) and axial fluid-sensitive reconstructed (b) MR images show a complete posterior root tear (arrow). (c) Arthroscopic image from Movie 3 shows a torn posterior root. Inset shows the arthroscopic field of view.



at least five different MR imaging signs: an absent bow tie, a fragment within the intercondylar notch, a double PCL, a double anterior horn or flipped meniscus, and a disproportionally small posterior horn (Fig 18) (66–69). A bucket-handle tear of the LM can rarely manifest with a double ACL sign, where the fragment is located just posterior to the ACL (70). Although these signs are sensitive, they are not specific. For example, the absent bow-tie sign, where the innermost bow tie is not present, can also be seen in a small or pediatric patient and with a radial tear of the body, macerated meniscus, or prior partial meniscectomy (67). Similarly, mimics of the double PCL sign include a prominent ligament of Humphry, a meniscomeniscal ligament, and intercondylar osseous bodies (71).

meniscus should alert the interpreting physician to search for a displaced meniscal fragment.

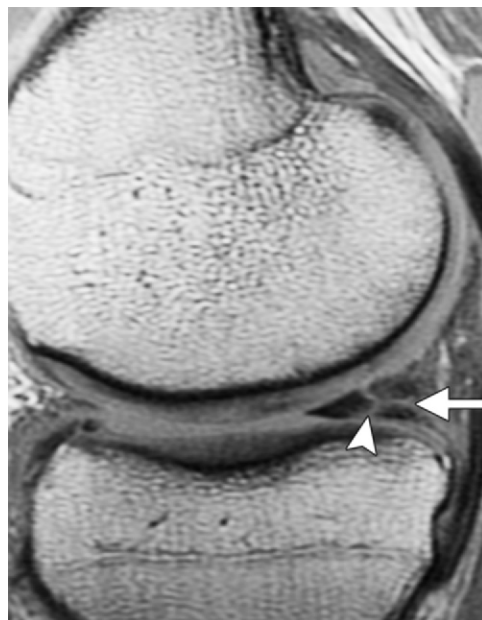
Bucket-Handle Tear

A bucket-handle tear is a longitudinal tear with central migration of the inner “handle” fragment (Fig 17, Movie 5). This tear pattern occurs seven times more frequently in the MM (65) and has

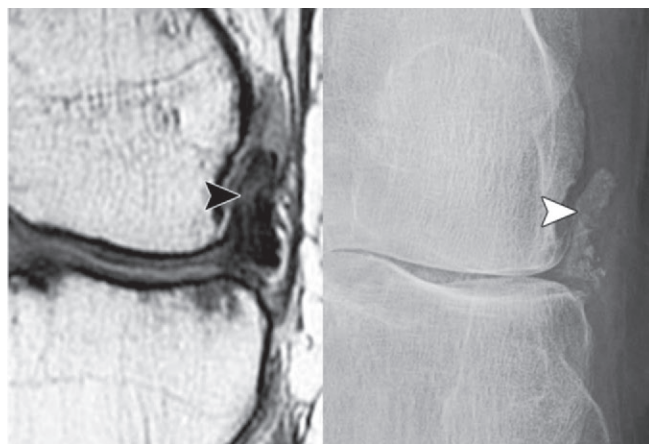
Fraying

At arthroscopy, *fraying* is defined as surface irregularity along the meniscal free edge without a discrete tear (Movie 6). In our experience, improved in-plane resolution and thinner sections have

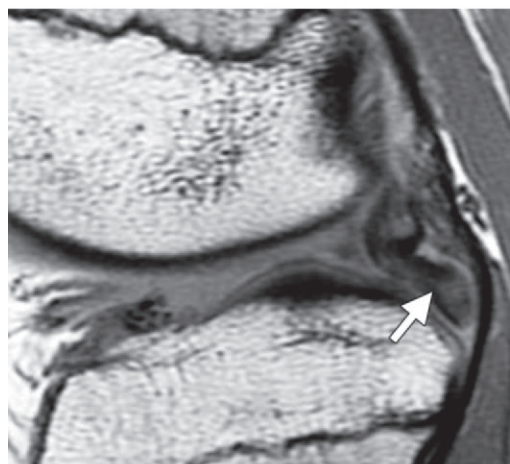
Figure 15. Complex tear. Sagittal PD-weighted MR image shows both vertical (arrowhead) and horizontal (arrow) components. Complex tears typically appear fragmented.



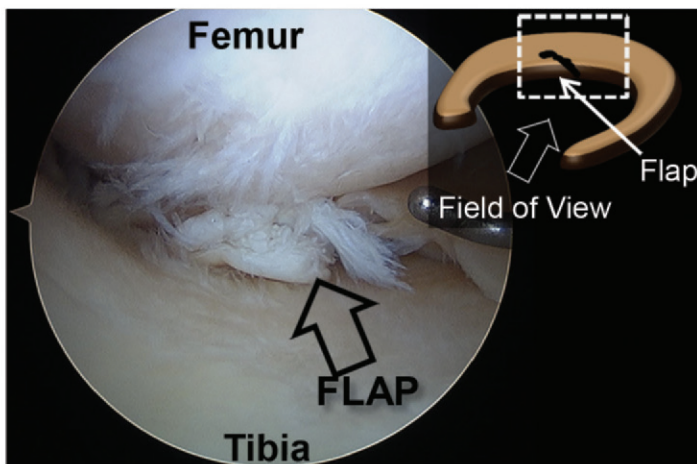
a.



c.



b.



d.

Figure 16. Displaced tear. (a) Coronal T2-weighted MR image shows a flipped fragment within the intercondylar notch (arrow) from a complex tear of the MM. (b) Sagittal PD-weighted MR image shows a large flipped fragment (arrow) in the popliteal recess from a torn LM. (c) Coronal PD-weighted MR image (left) and corresponding anteroposterior radiograph (right) show a laterally displaced meniscal fragment (arrowheads) extending into the superior recess, with central areas of chondrocalcinosis. (d) Arthroscopic image from Movie 4 shows a meniscal flap. Inset shows the arthroscopic field of view.

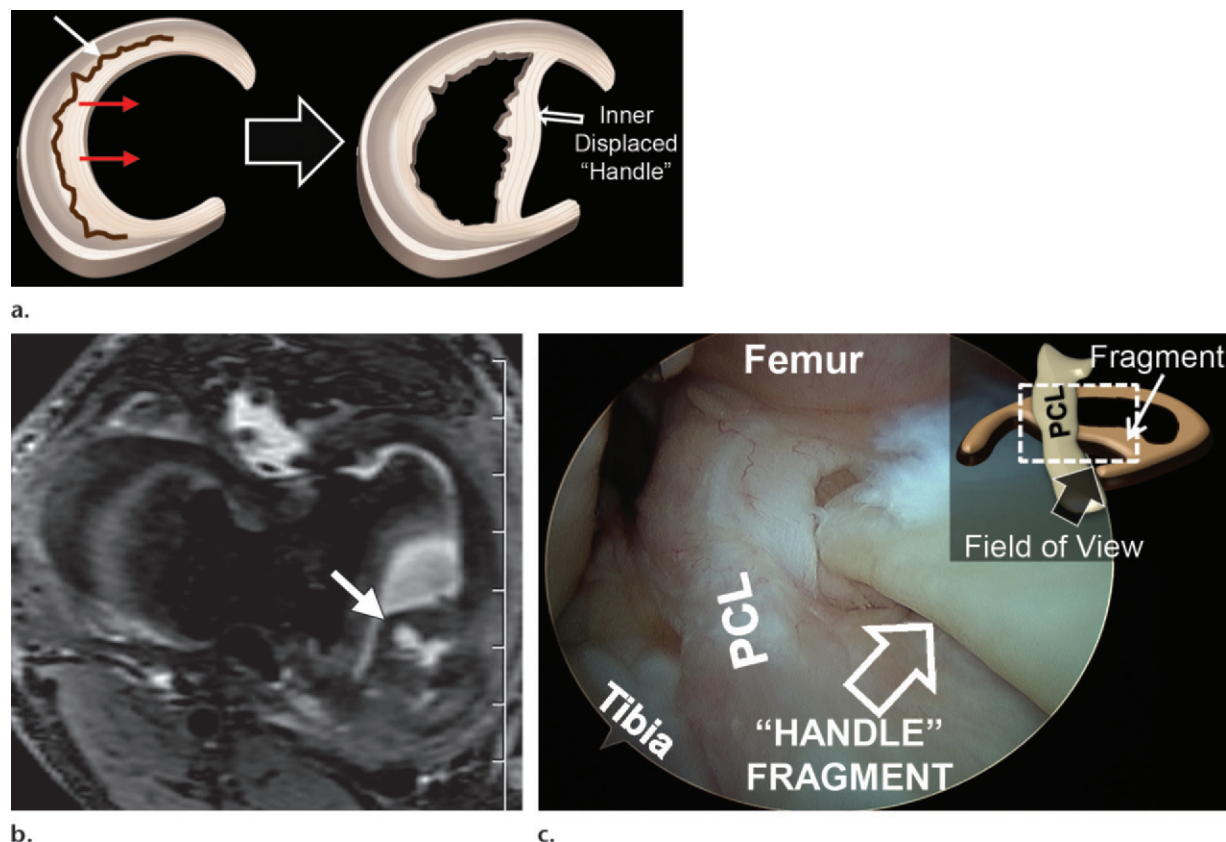


Figure 17. Bucket-handle tear. (a) Diagram shows a longitudinal tear (white arrow), with central displacement (red arrows) of the inner segment or “handle.” (b) Axial fluid-sensitive reconstructed MR image shows a rare bucket-handle tear that involves only about one-third of the meniscus (arrow). Typically this type of tear involves the majority of the meniscus. (c) Arthroscopic image from Movie 5 shows a centrally displaced torn meniscal fragment from a bucket-handle tear. Inset shows the arthroscopic field of view.

resulted in MR imaging depiction of areas of meniscal fraying, which can involve the free edge of the body, the posterior horn, or the posterior root ligaments. Equivocal and discordant cases are more commonly identified in the LM than in the MM (72). At MR imaging, the free edge may demonstrate loss of its sharp tapered central edge, and the posterior root ligaments may show subtle, ill-defined, horizontally oriented increased intrameniscal signal intensity contacting the articular surface (Fig 19). This latter finding within the posterior root ligament cannot be differentiated from a possible shallow partial-thickness tear, fraying, or surrounding synovitis. Although further research to distinguish fraying from partial-thickness tears is warranted, a differential diagnosis of synovitis, partial tear, or fraying can be used for equivocal findings in patients older than 40 years without an acute traumatic event. However, in younger patients after an acute trauma, LM posterior root amorphous increased signal intensity contacting the articular surface should be reported as a probable tear. More recently, the accuracy of MR imaging in diagnosing meniscal injuries in patients aged 50 years and older has

been evaluated, with reported sensitivities and specificities similar to those found in younger patients, when only definitive MR imaging findings were considered a tear (ie, the “two-touch-slice” rule). Specificity decreased if equivocal or probable findings were considered a tear, although the authors note that several indeterminate cases resulted in surgical débridement to a smooth margin at arthroscopy (72).

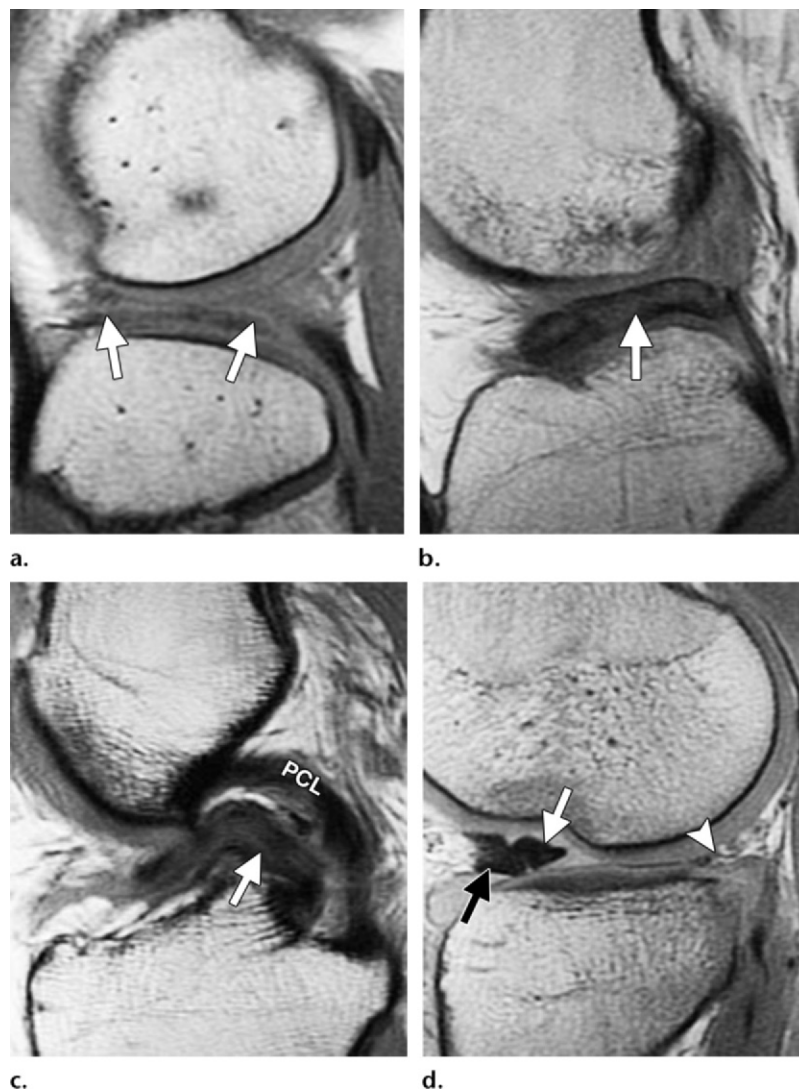
Indirect Signs of Meniscal Tear

Secondary or indirect signs of a meniscal tear are MR imaging findings that can accompany meniscal tears. In technically limited or equivocal cases, these signs can increase the reader’s diagnostic confidence. Although these indirect signs have low sensitivity, they have high specificity and high PPVs for an underlying tear. The most commonly used and better-established signs include a parameniscal cyst, meniscal extrusion, and subchondral marrow edema.

Parameniscal Cyst

Parameniscal cysts are distinguished from bursae and ganglion cysts by their intimate association

Figure 18. MR imaging signs of a bucket-handle tear. **(a)** Sagittal PD-weighted MR image shows the absent bow-tie sign, with nonvisualization of the meniscal body (arrows). **(b)** Sagittal PD-weighted MR image shows the fragment within the intercondylar notch sign, with a centrally displaced meniscal fragment (arrow) eccentric to the PCL. This finding is commonly seen with lateral tears because an intact ACL impedes the fragment from reaching the level of the PCL. **(c)** Sagittal PD-weighted MR image shows the double PCL sign, with a displaced fragment from the MM anterior and parallel to the PCL (arrow). **(d)** Sagittal PD-weighted MR image shows the double anterior horn sign, with a meniscal fragment (white arrow) posterior to and displacing the native anterior horn (black arrow) and a markedly diminutive posterior horn (arrowhead).



with the meniscus, either through direct contact or via a fluid track. They represent the peripheral escape of joint fluid through a meniscal tear, which typically contains a horizontal component (Fig 6b) (73). This sign has a PPV of more than 90%, with the exception of the anterior horn of the LM, where the PPV is 67% (74).

Meniscal Extrusion

Disruption of the circumferentially oriented collagen bundles results in the loss of the meniscal hoop strength and subsequent extrusion. Extrusion is present when the peripheral margin of the meniscus extends 3 mm or more beyond the edge of the tibial plateau (Fig 20a). In the setting of hypertrophic bone spurs, the osteophyte should be excluded for determination of the outer margin of the tibial plateau. There is a close association between meniscal extrusion and root tears. Specifically, 76% of medial root tears have extrusion, and 39% of extrusions have medial root tears (59). However, meniscal extrusion can also

be seen with complex tears, large radial tears, and severe meniscal degeneration (75).

Subchondral Marrow Edema

Linear subchondral bone marrow edema, in contrast to the more nonspecific edema often seen with degenerative changes, is defined as superficial edema that is adjacent to the meniscal attachment site, parallels the articular surface, and is less than 5 mm deep (Fig 20b). This sign can be seen in more than 60% of MM tears and more than 90% of LM tears, with a sensitivity and specificity of 64%–70% and 94%–100% for the MM, respectively, and 88%–89% and 98%–100% for the LM, respectively (76). Similarly, Kaplan et al (77) found that 64% of bone bruises of the posterior medial tibial plateau have an associated tear of the MM posterior horn.

Diagnostic Errors

Diagnostic errors can be divided into false-negative and false-positive errors. False-negative

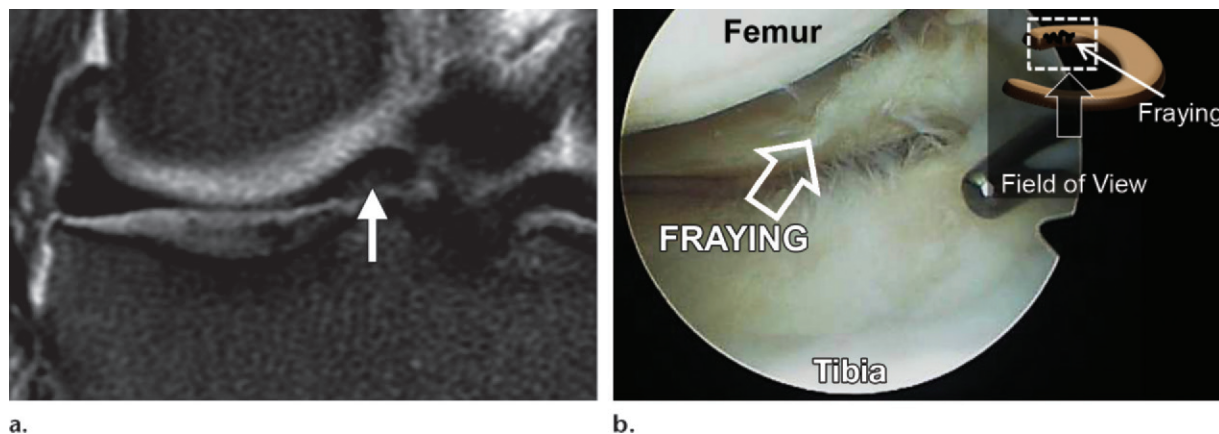


Figure 19. Meniscal fraying. (a) Coronal fat-suppressed PD-weighted MR image shows amorphous high signal intensity of the posterior root contacting the inferior articular surface (arrow), without a discrete cleft or distortion. (b) Arthroscopic image from Movie 6 shows free-edge surface irregularity. Inset shows the arthroscopic field of view.

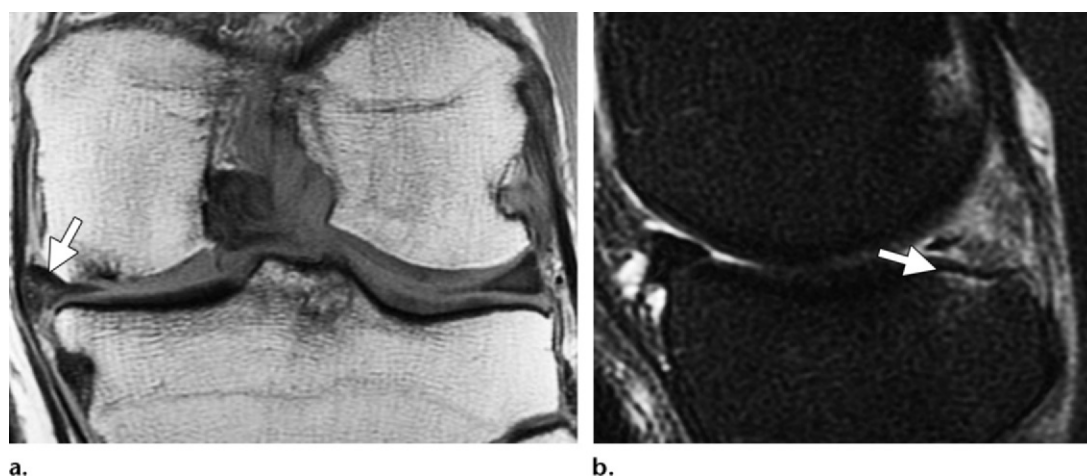


Figure 20. Indirect signs of meniscal tear. (a) Coronal PD-weighted MR image shows extrusion of the meniscal body (arrow) secondary to an underlying complex tear. (b) Sagittal T2-weighted MR image shows linear subchondral edema (arrow) associated with an adjacent meniscal tear.

errors commonly involve the LM, particularly when the tear is small and involves the posterior horn (4). These errors are either anatomic (tears are mistaken for normal anatomic structures) or technique related (arterial pulsation or magic-angle effect that obscures a tear). False-positive errors include mistaking normal anatomic structures and variants for a meniscal tear. Other causes include the magic-angle effect, healed tears, and limitations of arthroscopy. The magic-angle effect occurs when collagen fibers are oriented 55° relative to the magnetic field, which is often seen in the upslope medial segment of the LM posterior horn at imaging. This effect commonly occurs within the posterior horn and appears as amorphous increased signal intensity that does not extend to the articular surface, particularly on non-fluid-sensitive PD-weighted MR images (78). Healed tears can show retained abnormal increased signal intensity for an

undefined period. Clinical history, physical examination, and possible arthrography may help differentiate a healed tear from a possible new tear or re-tear.

Conclusion

With application of the “two-slice-touch” rule, MR imaging has high accuracy for preoperative detection of meniscal tears. In addition, MR imaging allows accurate characterization of various tear patterns, which can be instrumental for patient counseling and surgical planning. Familiarity with the normal anatomy, common anatomic variants, and indirect secondary signs of meniscal tears can help reduce interpretation errors.

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MR Imaging–based Diagnosis and Classification of Meniscal Tears

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A tear of the posterosuperior fascicle is highly associated with, but not specific for, a tear of the LM, with a sensitivity, specificity, and positive predictive value (PPV) of 89%, 96%, and 79%, respectively.

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MR imaging criteria for diagnosing a tear include meniscal distortion in the absence of prior surgery or increased intrasubstance signal intensity unequivocally contacting the articular surface. If these criteria are seen on two or more images, fulfilling the “two-slice-touch” rule, then the PPV for a tear is 94% in the MM and 96% in the LM, and the imaging findings should be reported as a meniscal tear.

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There is a close association between peripheral longitudinal tears and ACL tears. Specifically, 90% of MM and 83% of LM peripheral longitudinal tears have an associated ACL tear.

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The cleft sign is not specific and can be seen with both longitudinal and radial tears, depending on the location of the tear relative to the imaging plane.

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Secondary or indirect signs of a meniscal tear are MR imaging findings that can accompany meniscal tears. In technically limited or equivocal cases, these signs can increase the reader’s diagnostic confidence. Although these indirect signs have low sensitivity, they have high specificity and high PPVs for an underlying tear.