Meniscus: Anatomy, Function, and Dysfunction With Emphasis on Patterns of Failure

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The menisci of the knee are specialized fibrocartilaginous structures that serve a variety of functions ranging from femorotibial load transmission and shock absorption to joint lubrication and nutrient distribution. Meniscal tears represent an important cause of knee pain, occurring both as injuries in young athletes and as a degenerative condition in older persons. Symptoms related to such tears are the most common indication for arthroscopic knee surgery [1]. We review meniscal anatomy to promote an understanding of the appearance of the normal meniscus on MRI, to show that patterns of injury are dictated by the histologic structure of the meniscus, and to serve as an introduction to a description of the imaging appearance and classification system of the different types of meniscal tears, as well as imaging that leads to misdiagnosis and missed diagnosis.

Meniscal Structure and Function

The medial meniscus is a C-shaped structure, with a posterior horn that is wider than the anterior horn and a midportion sometimes referred to as the meniscal body [2] (Fig. 1). The medial meniscus is attached to the tibia by widely separated anterior and posterior root ligaments, the latter of which lies just anterior to the attachment of the posterior cruciate ligament (PCL) [2]. The point of tibial attachment of the anterior root ligament of the medial meniscus is more variable, with four distinct attachments described in the literature as at the intercondylar region, at the downward slope from the medial articular plateau, at the anterior slope of the tibial plateau, and no firm osseous attachment [3]. Additional stability related to the posterior horn of the medial meniscus is supplied by the posteromedial meniscocapsular and meniscotibial ligaments [4] and to the remainder of the medial meniscus by capsular attachments [2].

The lateral meniscus has a slightly different, more semicircular shape and covers a larger portion of the tibial articular surface than does the medial meniscus. The lateral meniscus is wider at its midportion than either the anterior or posterior horn. Like the medial meniscus, the lateral meniscus is attached to the tibia by anterior and posterior root ligaments, though these are closer together than on the medial side. The anterior root ligament of the lateral meniscus blends with fibers of the anterior cruciate ligament (ACL) as it attaches to the tibia. The posterior root ligament of the lateral meniscus can occasionally extend to the medial intercondylar tubercle and be mistaken for a bucket-handle meniscal tear when studied with MRI. A normal variant of the lateral meniscal attachments is characterized by a posterior attachment via a meniscofemoral ligament instead of an osseous attachment. Additional stability to the lateral meniscus is supplied by the lateral meniscotibial (coronary) ligament, popliteofibular ligament, and popliteomeniscal ligaments [5].

The medial and lateral menisci are connected anteriorly by the anterior transverse meniscomeniscal ligament. Both menisci are relatively avascular centrally and receive blood supply to the peripheral 10–25% of the meniscus from the perimeniscal plexus, which forms from branches of the lateral, medial, and middle genicular vessels [6]. Although the vascular peripheral zone and avascular central zone are not clearly distinguishable on conventional MRI sequences, newer imaging techniques using ultrashort TE (UTE) sequences may allow differentiation of the highly vascularized portions of the meniscus from those that are less vascular [7]. The vascularized peripheral portion of the meniscus has been referred to as the "red zone" and has important implications with regard to meniscal healing in the setting of a meniscal tear as well as after meniscal repair. Of note, there may be no red zone in the posterior horn of the lateral meniscus in the region of the popliteus tendon.

The major function of the menisci is to facilitate load transmission, with an estimated 45% of the applied load to the human femorotibial joint transmitted through the menisci [8]. The menisci also serve to increase congruity between the convex surfaces of the femoral condyles and the relatively flat apposing surfaces of the tibial plateaus, allowing increased mechanical stability. The medial meniscus has been shown to provide restraint against an-

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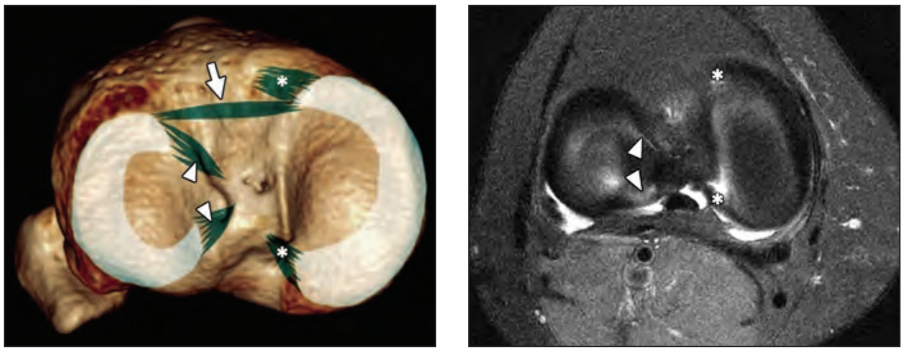
terior tibial translation in cadaveric knees under compressive loads [9, 10], and the posterior horn of the medial meniscus in particular has been shown to function as a secondary stabilizer of the knee joint in ACL-deficient knees [11].

Collagen Morphology

The collagen framework of the menisci allows them to function in load transmission, with the orientation of the collagen fibers determining the directions in which meniscal tissue can withstand tensile stress [12]. The normal meniscus is approximately 74% water, with collagen comprising 75% of the dry weight of meniscal tissue [13]. Most of the collagen in menisci is type I collagen, in contrast to the type II collagen that is evident in hyaline articular cartilage. At the meniscal surface, the collagen fibers are randomly oriented, but they create a strong envelope surrounding the meniscal substance referred to as the laminar layer. The central core of the meniscus is formed from two major types of collagen bundles: primarily peripherally located circumferentially aligned bundles, which are held together by predominantly centrally located radial tie fibers connecting the central portion to the peripheral portion of the meniscus [14–16].

Diagnostic Criteria for Meniscal Tears on MRI

A meniscal tear may be visualized on MRI as either an abnormality in the normal meniscal contour with a truncated or irregular appearance of the meniscal tissue or an abnormality of meniscal signal intensity with the presence of intermediate or high signal intensity that violates the surface of a meniscus [17]. Intrasubstance signal intensity that does not clearly extend to the meniscal surface may also be seen. According to studies with arthroscopic correlation, however, such nonsurfacing signal alteration typically corresponds to degeneration, normal variants, or tears that cannot be detected or treated arthroscopically [18, 19]. The specificity of MRI in diagnosing meniscal tears is also increased by requiring that signal intensity abnormality be seen on two or more images rather than a single image [20].



A B

Fig. 1—Normal meniscal structure.
A and **B,** Computer-generated (**A**) and MR (**B**) images show medial meniscus is C-shaped with wider posterior horn than anterior horn or midportion and with wide separation of anterior and posterior root ligaments (*asterisks*). Lateral meniscus is wider in its midportion than either anterior horn or posterior horn, and attachments of its anterior and posterior root ligaments (*arrowheads*) are closer together than on medial side. Two menisci are connected anteriorly by anterior transverse meniscomeniscal ligament (*arrow*, **A**).

There has been some variability in the literature regarding the terminology used to describe meniscal tears. To address these inconsistencies, the International Society of Arthroscopy, Knee Surgery and Orthopedic Sports Medicine (ISAKOS) formed a subcommittee on meniscal documentation in 2006 and proposed a classification system that is now widely used by surgeons and can be applied to MRI findings [21–23]. In this classification system, a meniscal tear is described in terms of its length, depth, radial location, rim width location, involvement near the popliteal hiatus, tear pattern, and quality of the background meniscal tissue [21]. With MRI, these features are typically best seen on coronal and sagittal non–fat-saturated and fat-saturated proton density–weighted or fat-saturated T2-weighted sequences [23].

Classification of Meniscal Tear Pattern

Nondisplaced Meniscal Tears

There are five basic types of meniscal tears, which are dictated by the type of applied force and the collagen structure: longitudinal horizontal, longitudinal vertical, longitudinal vertical oblique, radial, and radial oblique. The ISAKOS classification includes only three nondisplaced tear patterns: longitudinal vertical, horizontal, and radial [21]. Oblique tears are not included in the classification system but are described here to delineate the differences in meniscal tears with respect to collagen bundle orientation. The term “longitudinal” implies circumferential extension along the long axis of the meniscus. Most vertical and horizontal tears reveal such extension, whereas radial tears usually show central-peripheral extension alone or are combined with a lesser amount of circumferential extension.

Vertical longitudinal tears are common among symptomatic meniscal tears treated arthroscopically. Application of an axial compressive force tends to drive the meniscus out of the joint, a phenomenon known as hoop stress, but the meniscus is held in place by a number of structures, including the meniscal root ligaments. The result is an initial small microtear that is oriented along the axis of the hoop stress. This tear, as it encounters resistance from the longitudinally oriented peripheral collagen fibers, changes direction, taking the path of least resistance, and extends between the circumferentially aligned collagen bundles in the periphery, resulting in a longitudinal (circumferential) vertical tear. On MRI these tears are visualized as vertically oriented regions of intermediate or high signal intensity that violate at least one meniscal surface and remain approximately the same distance from the edge of the meniscus throughout their entire course (Figs. 2A and 2B). These tears tend to involve the outer half of the meniscus. With higher-energy mechanisms, the tear may become obliquely oriented, violating some of the circumferential collagen bundles and resulting in what is designated a longitudinal vertical oblique tear (Fig. 2C).

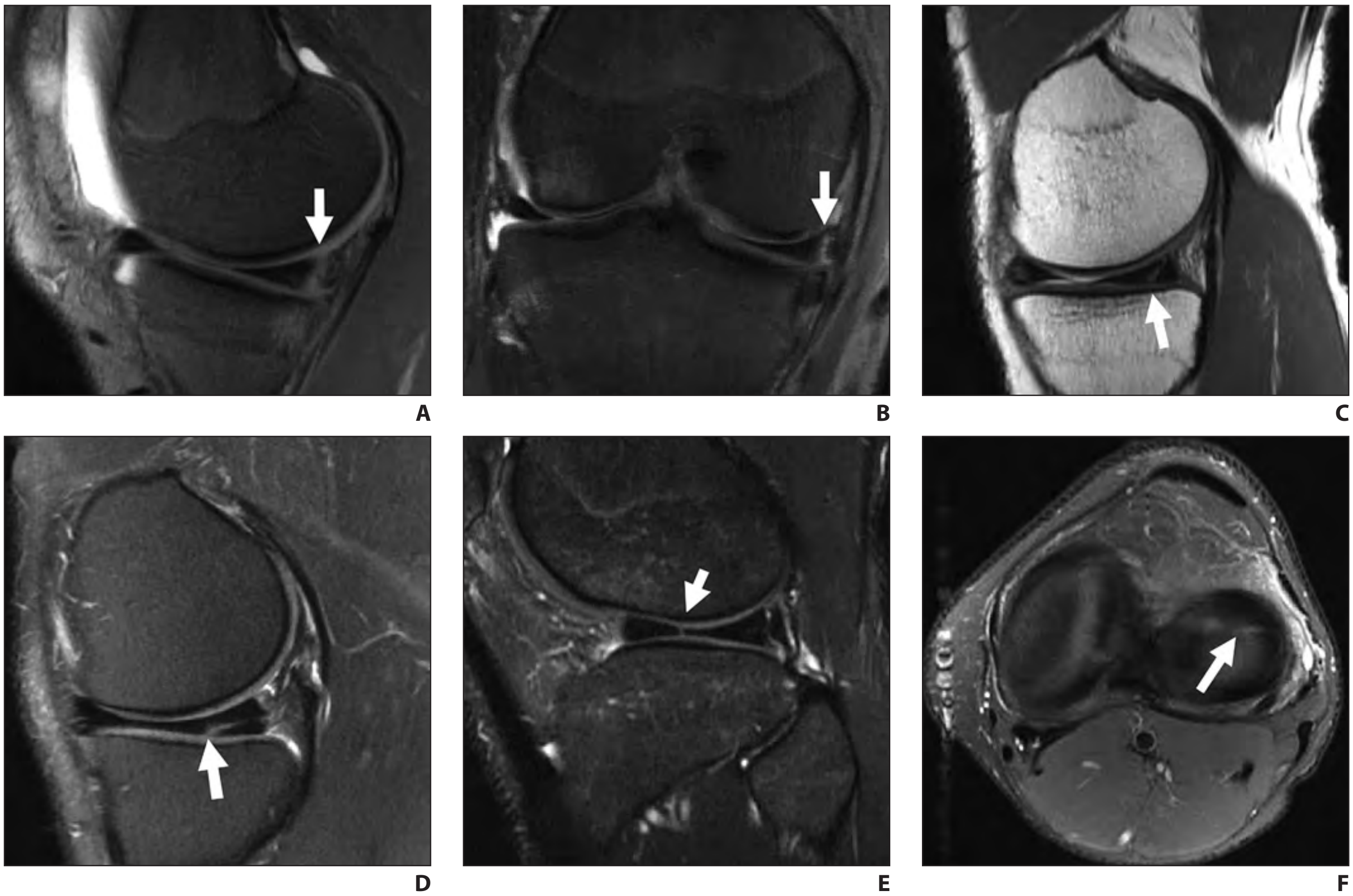


Fig. 2—Basic patterns of meniscal tear.
A and **B,** Sagittal (**A**) and coronal (**B**) T2-weighted fat-saturated MR images show longitudinal vertical tears (*arrows*) as vertically oriented linear regions of intermediate or high signal intensity.
C, Sagittal MR image shows longitudinal vertical oblique meniscal tear (*arrow*) of posterior horn of medial meniscus as obliquely oriented region of altered signal intensity violating both meniscal surfaces.
D, Sagittal T2-weighted fat-saturated MR image shows longitudinal horizontal tear (*arrow*) of posterior horn of medial meniscus as transversely oriented region of altered signal intensity parallel to articular surface that violates inferior meniscal surface.
E and **F,** Sagittal (**E**) and axial (**F**) MR images perpendicular to long axis of meniscus show radial tear at junction of anterior horn and body of lateral meniscus (*arrows*) as linear signal intensity.

(Fig. 2 continues on the next page)

Longitudinal horizontal tears begin at or near the inner margin, or free edge, of the meniscus and extend in a transverse fashion toward the meniscal periphery, usually following the path of least resistance between and not through the circumferential collagen bundles. These tears result when a shear force is applied tangent to the surface of the meniscus, such as during a rotational knee injury, resulting in a tear in a similar horizontal plane as the applied force. Longitudinal horizontal tears are frequently associated with parameniscal cysts, with 88% of such cysts being located adjacent to a tear with a longitudinal horizontal component [24]. On MRI, a longitudinal horizontal tear will appear as a linear horizontally or transversely oriented region of high signal intensity in either the coronal or sagittal plane or in both of these planes (Fig. 2D).

A radial tear is oriented perpendicular to the long axis of the circumferential collagen bundles, along the path of the radial tie fibers [25]. Like longitudinal horizontal tears, radial tears commonly result from shear forces applied tangent to the surface of the meniscus. Radial tears are best displayed on axial images (Figs. 2E and 2F). In the sagittal and coronal planes, they may present as an absent meniscus on a single slice that corresponds to a meniscal gap created by the tear. When the tear also extends in the direction of the circumferential bundles rather than only orthogonal to them, a radial oblique tear results, often designated a parrot-beak tear. These are visible as a "marching cleft" sign on MRI (Figs. 2G–2I).

Displaced Meniscal Tears

Although the menisci are normally stable in position because of the combination of capsular and root ligament attachments, meniscal tissue may become displaced in a variety of directions and locations in the setting of a meniscal tear. Longitudinal vertical tears that have a significant circumferential dimension violate an increasing number of radial tie fibers and are more likely to displace centrally, producing a bucket-handle tear (Figs. 3A–3C). When this occurs with a medial meniscal tear, the displaced tissue may produce a "double PCL" sign. When the lateral meniscus is involved, a pseudo-

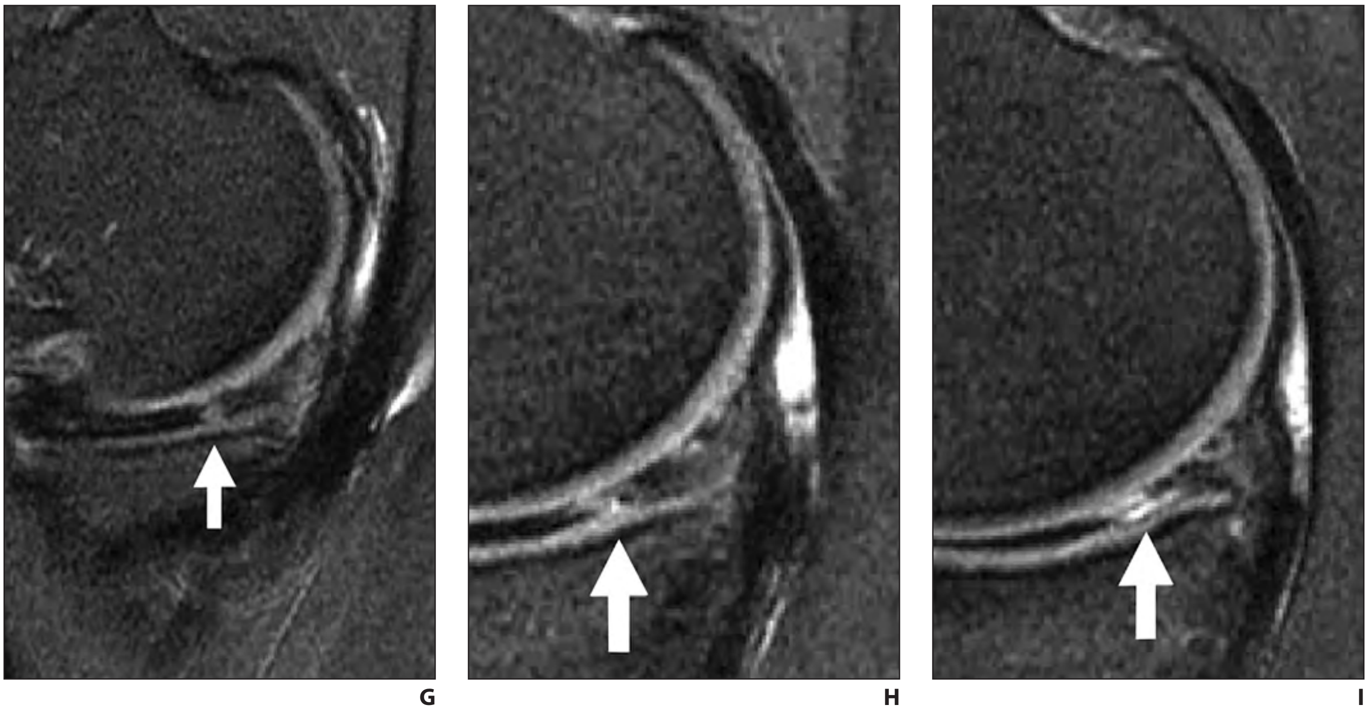


Fig. 2 (continued)—Basic patterns of meniscal tear.
G–I, Sequential sagittal T2-weighted fat-saturated MR images show radial oblique tear (*arrows*) extends orthogonal to axis of meniscus and of circumferential collagen fibers but also extends in their direction, creating "marching cleft" sign.

tear of the ACL may result. If the centrally displaced flap of a bucket-handle tear progressively inverts as the peripheral rim of tissue rotates centrally and superiorly, the femoral condyle may become entrapped by the inverted meniscal tissue. If the centrally displaced meniscal flap is torn, a "broken handle" tear results. If the peripheral rim of meniscal tissue is torn, the result is a "leaking bucket" tear.

Displaced longitudinal vertical meniscal tears are typically reduced and reattached to prevent symptoms of knee locking. Successful reparability is predicted by the nondisplaced peripheral rim of tissue measuring less than 4 mm in thickness, indicating a tear in or near the red zone of the meniscus; a tear greater than 9 mm in length; and normal signal of the displaced inner flap of meniscal tissue [26].

When a longitudinal horizontal tear displaces, the result is a meniscal flap (Figs. 3D and 3E). If the flap rotates peripherally, it can lead to gradual erosion of the subjacent bone in the tibial or femoral condyle.

Root Ligament Abnormalities

In addition to tears of the meniscal tissue proper, injuries can also occur within the meniscal root ligaments. Tears of the posterior root ligament of the medial meniscus are common, found in 10–21% of arthroscopic meniscal repairs [27] (Figs. 4A and 4B). These may result in peripheral extrusion of the meniscal body, which in turn causes bowing of the tibial collateral ligament (medial collateral ligament [MCL]), with cartilage loss and edema in the uncovered portion of the ipsilateral tibial plateau. A tear of the posterior root ligament of the medial meniscus can generally be distinguished from a radial tear of the adjacent posterior horn of the medial meniscus by the relatively smooth margin of the latter and the nodular appearance of the former. Tears of the meniscal root ligaments can be classified by the system introduced by LaPrade et al. [28]. According to this system, a type 1 tear is a partial meniscal tear within 9 mm of the root attachment, type 2 is a complete radial meniscal tear, type 3 is a bucket-handle tear with meniscal root detachment, type 4 is a complex oblique meniscal tear extending into the root attachment, and type 5 is an avulsion of the meniscal root attachment. Type 2 tears are further subdivided into subtype A, B, or C by the distance of the tear from the root attachment.

Avulsion injuries at the attachment of the posterior root ligament of the medial meniscus (LaPrade type 5) may result in the development of a meniscal ossicle [29, 30]. Such ossicles, however, may also be developmental rather than pathologic in pathogenesis. Tears of the posterior root ligament of the medial meniscus can also be associated with a meniscal flounce, which appears as an undulation of the inner margin of the meniscus.

Injuries can also involve the popliteomeniscal ligaments, which normally attach the posterior horn of the lateral meniscus to the posterolateral aspect of the joint capsule near the intraarticular portion of the popliteus tendon and which provide important stability to the posterior horn of the lateral meniscus. There are normally three popliteomeniscal ligaments in most persons: the lateral-most anteroinferior ligament, the posterosuperior ligament, and the medial-most posteroinferior ligament. Tearing of these ligaments, which commonly occurs in the setting of ACL injury, may allow the posterior horn of the meniscus to displace anteriorly, sometimes assuming a position adjacent to the anterior horn of the lateral meniscus.

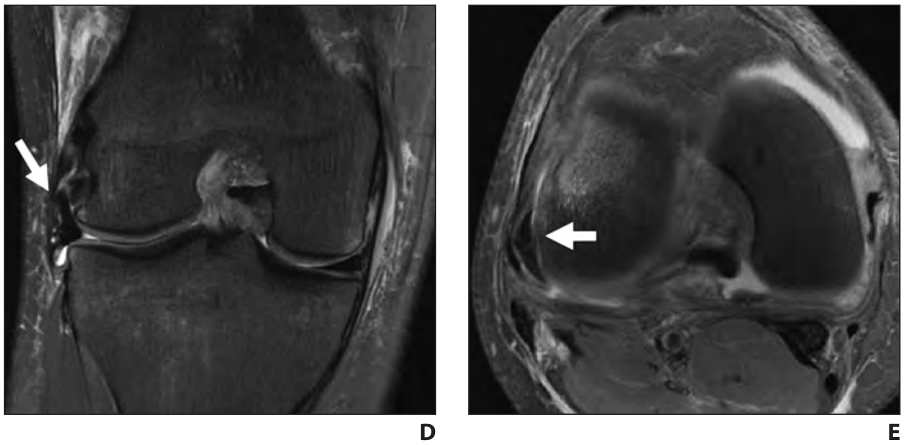


Fig. 3—Displaced meniscal tears include both bucket-handle and flap tears.
A–C, 37-year-old woman had medial knee pain and swelling after dancing injury. Coronal (**A**), sagittal (**B**), and axial (**C**) T2-weighted fat-saturated MR images show bucket-handle tear of medial meniscus with truncated appearance of body of medial meniscus (*arrowhead*, **A** and **C**) and displaced meniscal tissue in intercondylar notch (*arrows*).
D and **E,** 23-year-old woman had contact injury to right knee while playing soccer. Coronal (**D**) and axial (**E**) T2-weighted fat-saturated MR images show tear of body of lateral meniscus, which has diminutive appearance, with torn flap (*arrows*) displaced superiorly adjacent to lateral femoral condyle.

Combined Meniscal–Ligamentous Failure

Meniscal tears are common in the setting of injury to the ACL, with as many as 43% of ACL injuries showing an associated injury of either the lateral or medial meniscus [31] and with cadaveric studies showing meniscal lesions in 60% of persons with ACL tears [32]. In particular, injury to the peripheral attachment of the posterior horn of the medial meniscus (i.e., a meniscal ramp lesion) occurs in 9–17% of ACL tears [31] (Figs. 5A and 5B). Even if there is no visible tear on conventional MRI, the menisci may be intrinsically abnormal after ACL tear, as evidenced by increased T2* values of the menisci of ACL-injured subjects imaged with UTE sequences [33]. Unfortunately, sensitivity for medial and lateral meniscal tears is also decreased in the presence of an ACL tear, which may be a result, at least in part, of the fact that meniscal tears associated with ACL injury are in locations in which tears are difficult to display, identify, or diagnose, such as the posterior horn of the lateral meniscus [34].

Fig. 4—Root ligament tear of 40-year-old woman who had left knee pain for 9 months.
A and **B,** Coronal T2-weighted fat-saturated MR images show partial radial tear of medial meniscus at posterior root ligament attachment (*arrow*, **A**), with accompanying degeneration of posterior root ligament and resultant peripheral extrusion of body of medial meniscus (*arrowhead*, **B**) with bowing and thickening of medial collateral ligament.

The combination of both ACL and MCL injury is also associated with meniscal injury. O'Donoghue [35, 36] originally described an unhappy triad consisting of an ACL tear, tears of both the superficial and deep portions of the MCL, and rupture of the medial meniscus. Subsequent literature has shown that injury to the lateral meniscus is the more common meniscal injury [37]. Particular attention, therefore, should be paid to the medial meniscus, especially because studies have shown that sensitivity for medial meniscal tears is decreased as the number of injuries to concomitant supporting structures increases [38].

Differential Diagnostic Considerations

MRI has a high sensitivity in the assessment of meniscal tears, with early research showing patients who underwent both MRI and arthroscopy with NPV for MRI of nearly 100% [39], and with subsequent research showing that MRI could allow correct characterization of meniscal tear types in almost 80% of cases as compared with an arthroscopic standard [40]. There are numerous anatomic structures, physiologic effects, and pathologic conditions, however, that may simulate meniscal tears and limit the specificity of MRI. A short review of some of these structures, effects, and pathologic conditions is included here.

Anatomic Structures

The normal anteroinferior, posterosuperior, and posteroinferior popliteomeniscal ligaments are intimate with the popliteal hiatus and subpopliteal recess. Joint fluid extending into the hiatus or recess, or both areas, can lead to altered signal intensity adjacent to the peripheral portion of the posterior horn of the lateral meniscus, simulating a meniscal tear [41, 42]. Similarly, the meniscofemoral ligaments of Humphry and Wrisberg may also simulate a tear of the posterior horn of the lateral meniscus because the loose connective tissue between one or both of these ligaments and the meniscal tissue may resemble the appearance of a longitudinal vertical tear [42–45]. The anterior, posterior, and oblique meniscomeniscal ligaments can also simulate a meniscal tear, especially the anterior transverse meniscomeniscal ligament that may resemble a tear of the anterior horn of the lateral meniscus, or the less common oblique meniscomeniscal ligaments that may simulate centrally displaced meniscal tissue [42, 44]. Additionally, normal meniscal recesses, which are typically more prominent laterally than medially, leading to greater mobility of the lateral meniscus, can be mistaken for a meniscocapsular tear [30].

Physiologic Effects

The meniscal flounce can also be mistaken for a tear; the flounce represents a transient physiologic ruffling of the inner margin of the meniscus and, more frequently, the medial meniscus that commonly occurs when the knee is in a flexed position, [30]. Conversely, flouncelike folds in the menisci caused by true meniscal tears may be misinterpreted as physiologic meniscal flounces. One report of 3159 MRI studies of the knee performed over 2 years showed six meniscal flounces and four cases of flouncelike folds related to meniscal tears [45].

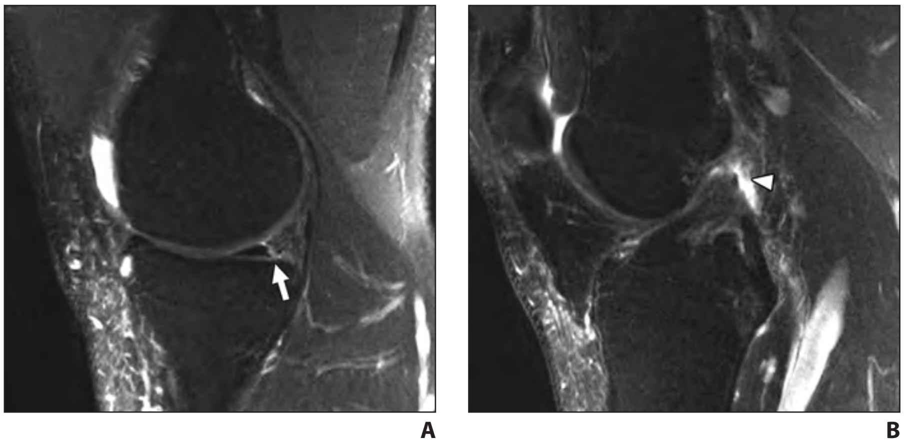


Fig. 5—Meniscal ramp lesion in 31-year-old man who heard "pop" sound in his left knee.
A and **B,** Sagittal T2-weighted fat-saturated MR images show meniscal ramp lesion (*arrow*, **A**), which is partial tear of posterior horn of medial meniscus at its peripheral attachment, with concomitant complete tear of anterior cruciate ligament (*arrowhead*, **B**).

Pathologic Conditions

In some pathologic situations, gas or calcium is present in or around meniscal tissue that may also simulate meniscal tears. Gas may be present in the joint lumen or within a degenerated meniscus, leading to a vacuum phenomenon and regional artifact that either obscure the meniscus or lead to an appearance resembling a meniscal tear [46]. Calcium pyrophosphate dihydrate (CPPD) crystal deposition disease can result in calcium deposition, or chondrocalcinosis, in the meniscal tissue, which may cause T1 shortening owing to the properties of the crystals themselves or to the associated meniscal degeneration and reactive changes surrounding the crystal deposits, simulating a meniscal tear [47]. In the presence of chondrocalcinosis involving the menisci, the sensitivity, specificity, and accuracy of MRI for the diagnosis of meniscal tears are decreased [48].

Postoperative Meniscus

Correlation with prior surgical history or imaging, if available, or with stigmata of prior surgery, such as scarring in the Hoffa fat pad, is important to avoid misdiagnosis of a normal postoperative appearance as evidence of a meniscal tear. Abnormalities in meniscal contour may be seen in the setting of prior partial meniscectomy, and abnormalities in meniscal signal intensity may be seen with prior meniscal repair. Features that more strongly suggest a new or residual tear include imbibition of native joint fluid or contrast agent (after arthrography) on the meniscal surface or frank extension of the fluid or contrast agent into the meniscal tissue [49].

MRI Artifacts

Imaging artifacts can also lead to apparent altered signal intensity within the meniscal tissue that may simulate a tear. Truncation artifact, resulting from changes in signal intensity at tissue interfaces, may produce artifactual areas of alternating linear high and low signal intensity. Magic angle effect artifact may also cause an apparent increase in meniscal signal intensity when the collagen fibers within the menisci are oriented at 55° to the external magnetic field, a situation that is particularly frequent in the posterior horn of the menisci near their root attachments [49].

Summary

MRI is a sensitive, accurate, and noninvasive means of evaluating the menisci for tears. Understanding the histologic structure of the meniscus, especially the collagen framework, is important in the analysis of the many different types and patterns of nondisplaced and displaced meniscal tears as they are shown on MRI. The resulting alterations within and around the abnormal meniscus can be simulated by a number of anatomic structures, physiologic effects, and pathologic conditions. Furthermore, MRI analysis of the postoperative meniscus has its own unique challenges, especially when such analysis is attempted without a complete history or access to the operative report.

REFERENCES

1. Thompson SR. Diagnostic knee arthroscopy and partial meniscectomy. *JBJS Essent Surg Tech* 2016; 6:e7
2. Greis PE, Bardana DD, Holmstrom MC, Burks RT. Meniscal injury. I. Basic science and evaluation. *J Am Acad Orthop Surg* 2002; 10:168–176
3. Berlet GC, Fowler PJ. The anterior horn of the medial meniscus. *Am J Sports Med* 1998; 26:540–543
4. DePhillipo NN, Moatshe G, Chahla J, et al. Quantitative and qualitative assessment of the posterior medial meniscus anatomy: defining meniscal ramp lesions. *Am J Sports Med* 2019; 47:372–378
5. Masferrer-Pino A, Saenz-Navarro I, Rojas G, et al. The menisco-tibio-popliteus-fibular complex: anatomic description of the structures that could avoid lateral meniscal extrusion. *Arthroscopy* 2020; 36:1917–1925
6. Arnoczky SP, Warren RF. Microvasculature of the human meniscus. *Am J Sports Med* 1982; 10:90–95
7. Chang EY, Du J, Chung CB. UTE imaging in the musculoskeletal system. *J Magn Reson Imaging* 2015; 41:870–883
8. Shrive NG, O'Connor JJ, Goodfellow JW. Load-bearing in the knee joint. *Clin Orthop Relat Res* 1978;131:279–287
9. Reynolds RJ, Walker PS, Buza J. Mechanisms of anterior-posterior stability of the knee joint under load-bearing. *J Biomech* 2017; 57:39–45
10. Walker PS, Arno S, Bell C, Salvadore G, Borukhov I, Oh C. Function of the medial meniscus in force transmission and stability. *J Biomech* 2015; 48:1383–1388
11. Gupta R, Kapoor A, Mittal N, Soni A, Khatri S, Masih GD. The role of meniscal tears and meniscectomy in the mechanical stability of the anterior cruciate ligament deficient knee. *Knee* 2018; 25:1051–1056
12. Aspden RM, Yarker YE, Hukins DW. Collagen orientations in the meniscus of the knee joint. *J Anat* 1985; 140:371–380
13. Allen AA, Caldwell GL, Fu FH. Anatomy and biomechanics of the meniscus. *Oper Tech Orthop* 1995; 5:2–9
14. Beaupré A. Choukroun R, Guidouin R, Garneau R, Gérardin H, Cardou A. Knee menisci: correlation between microstructure and biomechanics. *Clin Orthop Relat Res* 1986; 208:72–75
15. Morejon A, Norberg CD, De Rosa M, Best TM, Jackson AR, Travascio F. Compressive properties and hydraulic permeability of human meniscus: relationships with tissue structure and composition. *Front Bioeng Biotechnol* 2021; 8
16. Bullough PG, Munuera L, Murphy J, Weinstein AM. The strength of the menisci of the knee as it relates to their fine structure. *J Bone Joint Surg Br* 1970; 52:564–570
17. De Smet AA, Norris MA, Yandow DR, Quintana FA, Graf BK, Keene JS. MR diagnosis of meniscal tears of the knee: importance of high signal in the meniscus that extends to the surface. *AJR* 1993; 161:101–107
18. Kaplan PA, Nelson NL, Garvin KL, Brown DE. MR of the knee: the significance of high signal in the meniscus that does not clearly extend to the surface. *AJR* 1991; 156:333–336
19. Crues JV 3rd, Mink J, Levy TL, Lotysch M, Stoller DW. Meniscal tears of the knee: accuracy of MR imaging. *Radiology* 1987; 164:445–448
20. De Smet AA, Tuite MJ. Use of the "two-slice-touch" rule for the MRI diagnosis of meniscal tears. *AJR* 2006; 187:911–914
21. Anderson AF; ISAKOS Knee Committee. The ISAKOS classification of meniscal tears. (newsletter) *ISAKOS Newsletter* 2010; 14:11–13
22. Shah J, Hlis R, Ashikyan O, et al. Correlation of meniscus tears on MRI and arthroscopy using the ISAKOS classification provides satisfactory intermethod and inter-rater reliability. *J ISAKOS Joint Disord Orthop Sports Med* 2020; 5:201–207
23. Wadhwa V, Omar H, Coyner K, Khazzam M, Robertson W, Chhabra A. ISAKOS classification of meniscal tears: illustration on 2D and 3D isotropic spin echo MR imaging. *Eur J Radiol* 2016; 85:15–24
24. Campbell SE, Sanders TG, Morrison WB. MR imaging of meniscal cysts. *AJR* 2001; 177:409–413
25. Tuckman GA, Miller WJ, Remo JW, Fritts HM, Rozansky MI. Radial tears of the menisci: MR findings. *AJR* 1994; 163:395–400
26. Thoreux P, Réty F, Nourissat G, et al. Bucket-handle meniscal lesions: magnetic resonance imaging criteria for reparability. *Arthroscopy* 2006; 22:954–961
27. Bhatia S, LaPrade CM, Ellman MB, LaPrade RF. Meniscal root tears: significance, diagnosis, and treatment. *Am J Sports Med* 2014; 42:3016–3030
28. LaPrade CM, James EW, Cram TR, Feagin JA, Engebretsen L, LaPrade RF. Meniscal root tears: a classification system based on tear morphology. *Am J Sports Med* 2015; 43:363–369
29. Berg EE. The meniscal ossicle: the consequence of a meniscal avulsion. *Arthroscopy* 1991; 7:241–243
30. Mohankumar R, Palisch A, Khan W, White LM, Morrison WB. Meniscal ossicle: posttraumatic origin and association with posterior meniscal root tears. *AJR* 2014; 203:1040–1046
31. Chahla J, Dean CS, Moatshe G, et al. Meniscal ramp lesions: anatomy, incidence, diagnosis, and treatment. *Orthop J Sports Med* 2016; 4:
32. Peltier A, Lording T, Maubisson L, Ballis R, Neyret P, Lustig S. The role of the meniscotibial ligament in posteromedial rotational knee stability. *Knee Surg Sports Traumatol Arthrosc* 2015; 23:2967–2973
33. Williams A, Qian Y, Golla S, Chu CR. UTE-T2* mapping detects sub-clinical meniscus injury after anterior cruciate ligament tear. *Osteoarthritis Cartilage* 2012; 20:486–494
34. De Smet AA, Graf BK. Meniscal tears missed on MR imaging: relationship to meniscal tear patterns and anterior cruciate ligament tears. *AJR* 1994; 162:905–911
35. O'Donoghue DH. Surgical treatment of fresh injuries to the major ligaments of the knee. *J Bone Joint Surg Am* 1950; 32:721–738
36. O'Donoghue DH. Surgical treatment of injuries to ligaments of the knee. *J Am Med Assoc* 1959; 169:1423–1431
37. Shelbourne KD, Nitz PA. The O'Donoghue triad revisited: combined knee injuries involving anterior cruciate and medial collateral ligament tears. *Am J Sports Med* 1991; 19:474–477
38. Rubin DA, Kettering JM, Towers JD, Britton CA. MR imaging of knees having isolated and combined ligament injuries. *AJR* 1998; 170:1207–1213
39. Reicher MA, Hartzman S, Duckwiler GR, Bassett LW, Anderson LJ, Gold RH. Meniscal injuries: detection using MR imaging. *Radiology* 1986; 159:753–757
40. Jee WH, McCauley TR, Kim JM, et al. Meniscal tear configurations: categorization with MR imaging. *AJR* 2003; 180:93–97
41. Mesgarzadeh M, Moyer R, Leder DS, et al. MR imaging of the knee: expanded classification and pitfalls to interpretation of meniscal tears. *RadioGraphics* 1993; 13:489–500
42. Nguyen JC, De Smet AA, Graf BK, Rosas HG. Imaging-based diagnosis and classification of meniscal tears. *RadioGraphics* 2014; 34:981–999
43. Vahey TN, Bennett HT, Arrington LE, Shelbourne KD, Ng J. MR imaging of the knee: pseudotear of the lateral meniscus caused by the meniscofemoral ligament. *AJR* 1990; 154:1237–1239
44. Watanabe AT, Carter BC, Teitelbaum GP, Seeger LL, Bradley WC. Normal variations in MR imaging of the knee: appearance and frequency. *AJR* 1989; 153:341–344
45. Yu JS, Cosgarea AJ, Kaeding CC, Wilson D. Meniscal flounce MR imaging. *Radiology* 1997; 203:513–515
46. Shogry ME, Pope TL. Vacuum phenomenon simulating meniscal or cartilaginous injury of the knee at MR imaging. *Radiology* 1991; 180:513–515
47. Burke BJ, Escobedo EM, Wilson AJ, Hunter JC. Chondrocalcinosis mimicking a meniscal tear on MR imaging. *AJR* 1998; 170:69–70
48. Kaushik S, Erickson JK, Palmer WE, Winalski CS, Kilpatrick SJ, Weissman BN. Effect of chondrocalcinosis on the MR imaging of knee menisci. *AJR* 2001; 177:905–909
49. Mohankumar R, White LM, Naraghi A. Pitfalls and pearls in MRI of the knee. *AJR* 2014; 203:516–530

SUGGESTED READING

1. De Smet AA, How I diagnose meniscal tears on knee MRI. *AJR* 2012; 199:481–499