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REVIEW

Meniscal pathology in children: differences and similarities with the adult meniscus

Michael L. Francavilla · Ricardo Restrepo · Kathryn W. Zamora · Vijaya Sarode · Stephen M. Swirsky · Douglas Mintz

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Abstract The normal meniscus undergoes typical developmental changes during childhood, reaching a mature adult appearance by approximately 10 years of age. In addition to recognizing normal meniscal appearances in children, identifying abnormalities — such as tears and the different types of discoid meniscus and meniscal cysts, as well as the surgical implications of these abnormalities — is vital in pediatric imaging. The reported incidence of meniscal tears in adolescents and young adults has increased because of increased sports participation and more widespread use of MRI. This review discusses the normal appearance of the pediatric meniscus, meniscal abnormalities, associated injuries, and prognostic indicators for repair.

Keywords Knee · Trauma · Meniscus · Meniscal cyst · Discoid meniscus · Magnetic resonance imaging · Child · Adolescent

Introduction

As more and more children participate in sports and recreational activities, there has been an increase in acute and overuse injuries [1, 2]. More than 7 million high school students participate in athletics annually and more than 4 million sports or recreational injuries are sustained by school-age children per year in the United States [3–5]. The knee is the body part most commonly injured as a consequence of childhood sports [1, 6, 7]. Common knee injuries include fractures, anterior cruciate ligament tears and meniscal tears [2, 7]. If not treated, these injuries can have negative consequences in children and adolescents such as decreased school attendance, loss of participation in organized sports and early degenerative joint disease leading to disability. The reported incidence of meniscal tears in adolescents and young adults has increased because of increased sports participation and more widespread use of MRI [8–10].

Pediatric and adolescent athletes differ from adults in several important ways that contribute to the increased vulnerability to injury of joints in children; children have decreased motor skills, open physes and more cartilaginous joints, for example [1, 4, 11]. Likewise children may not always be good historians, tend to cooperate less, and may have subtle findings on physical exam after trauma. Clinical evaluation and physical exam can be nonspecific for meniscal injuries in children [9]. Therefore radiographs and MRI are invaluable in the evaluation of knee injuries.

The American College of Radiology Appropriateness Criteria for acute trauma to the knee with focal tenderness, inability to bear weight, or effusion indicates a radiograph of the knee as the initial study, while a knee MRI may be appropriate in some situations [12]. MRI has high tissue contrast, detailed resolution and multiplanar capability, allowing the evaluation of soft tissue, cartilage and bones, making it the imaging modality of choice for suspected internal derangement. It allows for surgery to be reserved for treatment rather than diagnosis. In adults MRI of the knee has been reported to be more than 90% accurate for abnormalities such as meniscal and anterior cruciate ligament

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M. L. Francavilla · R. Restrepo (✉) · K. W. Zamora · V. Sarode
Department of Radiology, Miami Children's Hospital,
3100 SW 62nd Ave., Miami, FL 33155, USA
e-mail: ricardo.restrepo@mch.com

D. Mintz
Hospital for Special Surgery, New York, NY, USA

S. M. Swirsky
Department of Orthopedics, Miami Children's Hospital,
3100 SW 62nd Ave., Miami, FL 33155, USA

(ACL) tears and articular cartilage abnormalities [13–16]. MRI permits characterization and localization of meniscal pathology, which provides important information for the surgeon. Additionally, MRI may demonstrate the presence of a discoid meniscus and meniscal cysts. This article describes meniscal anatomy and physiology, normal appearance from birth until adolescence as well as meniscal abnormalities, including tears, cysts and the discoid meniscus.

Meniscal anatomy

The menisci are semilunar fibrocartilaginous structures that are angled inward like wedges [17]. Situated between the femoral condyles and tibial plateaus, they serve a number of functions in the joint, including shock absorption, joint stabilization, joint lubrication and proprioception [13, 17–19]. The U-shape medial meniscus is larger, covers 50% of the medial tibial plateau, and has a more prominent posterior than anterior horn, whereas the lateral meniscus has a C shape with symmetrical anterior and posterior horns, which cover up to 70% of the tibial plateau [13, 17–19].

The medial meniscus is more firmly attached to the joint capsule than the lateral meniscus and should always be attached to the medial collateral ligament (Fig. 1) [18]. This firmer attachment makes it less mobile and more susceptible to meniscocapsular separation and tears. The anterior horn of the medial meniscus attaches to the bony tibial plateau anterior to the anterior cruciate ligament insertion. The posterior horn attaches to the tibial plateau anterior to the posterior cruciate ligament (PCL). The meniscotibial ligament, also known as the coronary ligament, and the meniscofemoral ligament are extensions of the deep fibers of the medial collateral ligament that attach the medial meniscus to the medial tibial plateau and medial femoral condyle, respectively (Fig. 1) [17, 20, 21].

The lateral meniscus has less restrictive attachments, allowing for greater translation [18]. The anterior horn of the lateral meniscus attaches to the tibial plateau and has fibers of the ACL that extend into it at the anterior attachment (root). Unlike the medial meniscus, the lateral meniscus has no attachment to the lateral collateral ligament (LCL). The posterior horn of the lateral meniscus is stabilized by the anteroinferior, posterosuperior and posteroinferior popliteomeniscal fascicles (Fig. 2) [17, 22, 23]. The anteroinferior fascicle fuses with the popliteofibular ligament to attach onto the styloid process of the fibula and the posterosuperior fascicle attaches onto the posterior joint capsule. The posteroinferior popliteomeniscal fascicle originates from the inferior margin of the posterior horn and attaches on the medial aponeurosis of the popliteus muscle. Johnson and De Smet [24] found that 97% of patients with an intact lateral meniscus have at least one visualized popliteomeniscal fascicle. Peduto et al. [23] showed that the posteroinferior fascicle is the least frequently visualized fascicle, seen by MRI in only 4 of 10 studied cadaveric knees. In addition to the popliteomeniscal fascicles, two other accessory posterior meniscofemoral ligaments are present in 66–93% of patients [18]. These are the variably present anterior ligament of Humphry and the posterior meniscofemoral ligament of Wrisberg, which course anteriorly and posteriorly to the PCL, respectively [25]. Furthermore, the menisci may be attached together anteriorly by the transverse intermeniscal ligament. These meniscofemoral and intermeniscal ligaments can create an interface with the meniscus that can be mistaken for meniscal tears and is therefore important to recognize. Other intra-articular intermeniscal ligaments are less common and less constant.

Meniscal vascularity and physiology

The medial and lateral geniculate arteries, branches of the popliteal artery, supply the medial and lateral menisci,

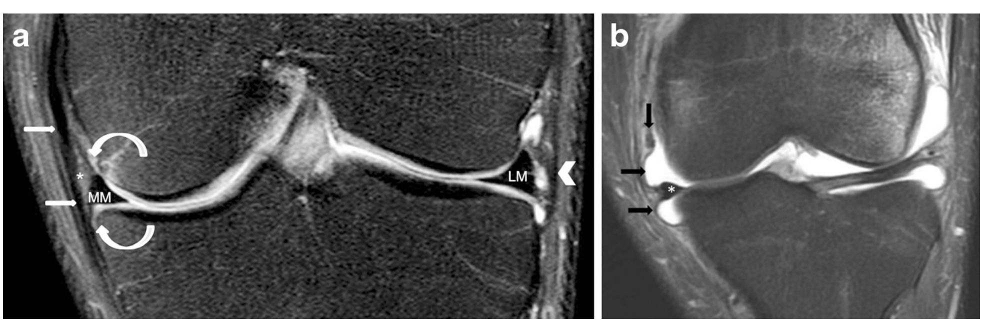


Fig. 1 Normal meniscotibial and meniscofemoral ligaments. **a** Coronal proton-density fat-suppressed image in a 17-year-old asymptomatic girl shows the deep fibers of a normal medial collateral ligament (MCL) (*arrows*) closely apposed to the medial meniscus (*MM*) with a tiny amount of fat (*asterisk*) interposed in between the structures. The meniscofemoral and meniscotibial ligaments are unusually well visualized (*curved arrows*). Note the normal significant separation between the lateral meniscus (*LM*) and the lateral collateral ligament (iliotibial band, *arrowhead*). **b** Coronal proton-density fat-suppressed image in a 17-year-old boy shows a joint effusion making the meniscotibial and meniscofemoral ligaments more conspicuous (*horizontal arrows*). Both ligaments are well attached to the extruded medial meniscus (*asterisk*). There is a cortical avulsion (*vertical arrow*) at the femoral insertion of the meniscofemoral ligament with no significant bone edema typical of cortical avulsions

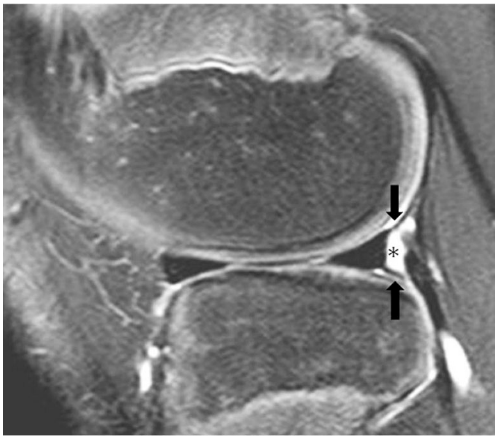


Fig. 2 Normal popliteomeniscal fascicles of the lateral meniscus in a 9-year-old boy. Sagittal T2-W fat-suppressed MR image shows a small amount of fluid (*asterisk*) at the popliteus hiatus outlining the superior and inferior popliteomeniscal fascicles (*arrows*)

respectively. At birth the menisci are vascularized throughout their substance. The intrameniscal vascularity gradually decreases centrally until it reaches the adult pattern by approximately 10 years of age [9, 25–27]. The intrameniscal vascularity is better visualized in children (Fig. 3), where it is seen as high signal on proton-density, T1- and T2-weighted images and can be linear. When it is linear, it may be confused with a meniscal tear, but vascularity should not contact an articular surface [27]. In the mature meniscus, the distribution of the vascularity is peripheral. The peripheral red zone — the outer 10–30% of the meniscus — remains vascular, while the inner 70–90% — called the white zone — is essentially avascular. In between there is a middle transitional zone (termed red–white zone) of intermediate vascularity. The red zone, because of its rich blood supply, demonstrates relatively good healing potential [26, 28]. The white zone, which is nourished only by passive diffusion, heals poorly, thus tears in this area tend to propagate and usually require intervention [10].

The menisci are primarily composed of densely packed fibroblasts and collagen. Prior to 3 months of age the menisci predominantly contain cells that have large cytoplasm-to-nucleus ratios. Between 3 months and 9 months of age the ratio of cytoplasm to the size of the nuclei decreases and the amount of collagen increases, but there is not yet a cartilaginous intercellular matrix. Starting at 3 years of age the ultrastructure of the menisci begins to transform with most collagen fibers arranged circumferentially, parallel to the long axis of the meniscus. Occasional fibers in the radial direction can be observed and these fibers are mainly located near the articular surface. This process is completed at about 9 years old, when the menisci are predominantly composed of collagen rather than fibroblasts. The ultrastructure of the meniscus in children 10 years and older is similar to that of the adult meniscus and consists mostly of type I collagen fibers arranged circumferentially parallel to the long axis, with relatively few fibroblasts seen [25]. The longitudinal direction of the fibers allows for the dissipation of compressive forces and hoop stress. Radial fibers are also present near the articular and mid-substance to function as tie fibers and assist in resisting longitudinal stress [25, 26, 28, 29].

Meniscal signal in children

The menisci are normally low-signal-intensity structures on all sequences because of their organized collagen structure with few mobile protons, while tears appear as foci of high signal, often linear extending to an articular surface [30]. Identifying

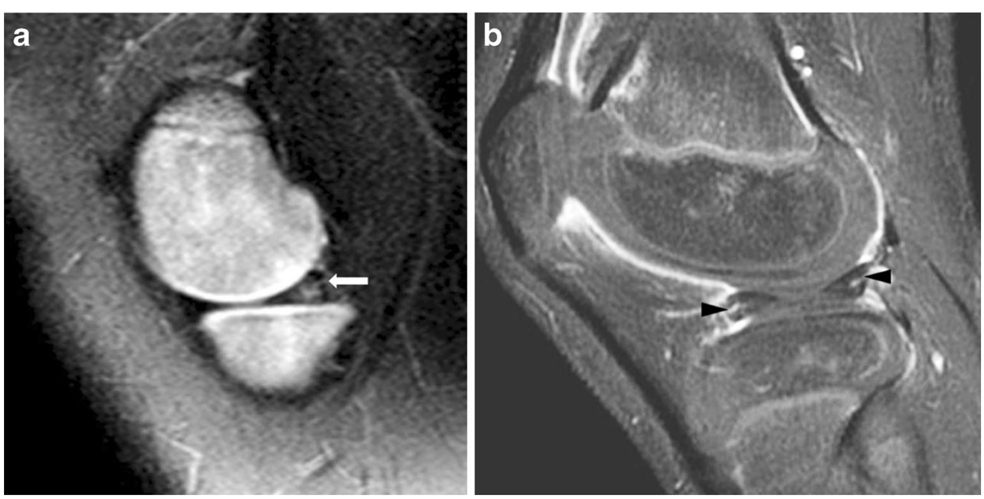


Fig. 3 Meniscal vascularity in children. **a** Sagittal proton-density fat-suppressed image of a 2-month-old girl's knee shows diffuse increased amorphous intrameniscal signal (*arrow*) involving most of the posterior horn of the medial meniscus but not touching the articular surface. **b** Sagittal contrast-enhanced T1-W fat-suppressed image of a 4-year-old boy's knee shows intrameniscal linear hyperintensities extending halfway into the meniscal substance (*arrowheads*) but not touching the articular surface. These findings are typical of intrameniscal vascularity at this age

tears is not always straightforward because there are other sources of high signal intensity in the menisci. For example, the posterior roots of the menisci can normally exhibit high signal intensity because of diverse attachment patterns [31, 32].

To assist with correct identification of a tear, meniscal signal was initially categorized into different grades. Meniscal signal grading by Crues et al. [33], with later modifications, is classified as follows: grade 0 consists of a normal, uniform low signal; grade 1 consists of an intrameniscal globular or ovoid signal that is not communicating with an articular surface (Fig. 4); grade 2 consists of an intrameniscal linear or wedge-shape signal that is not communicating with an articular surface (Fig. 4); grade 3a is an intrameniscal signal that equivocally contacts the articular surface; and grade 3b is an intrameniscal signal that clearly contacts the articular surface (Fig. 5). Only grade 3 signal represents a tear.

Grade 1 or grade 2 signal does not indicate a tear in either children or adults. High signal intensity on MRI that is not associated with a tear likely represents normal vascularity in children (Figs. 3 and 4) and myxoid degeneration in adults [34, 35]. A study by Takeda et al. [27] found that the prevalence of high signal intensity within the menisci unrelated to a tear on MRI was significantly higher in children than in adults, at the rates of 66% and 29%, respectively. High signal intensity in children was also shown to decrease with age; it was seen in approximately 60% of children younger than 13 years and only in approximately 30% of individuals older than 14 years. This high signal intensity in the pediatric meniscus not related to meniscal tear was most commonly observed in the posterior horn of the medial meniscus, concurring with the authors' experience [27].

Meniscal tear demographics and commonly associated injuries

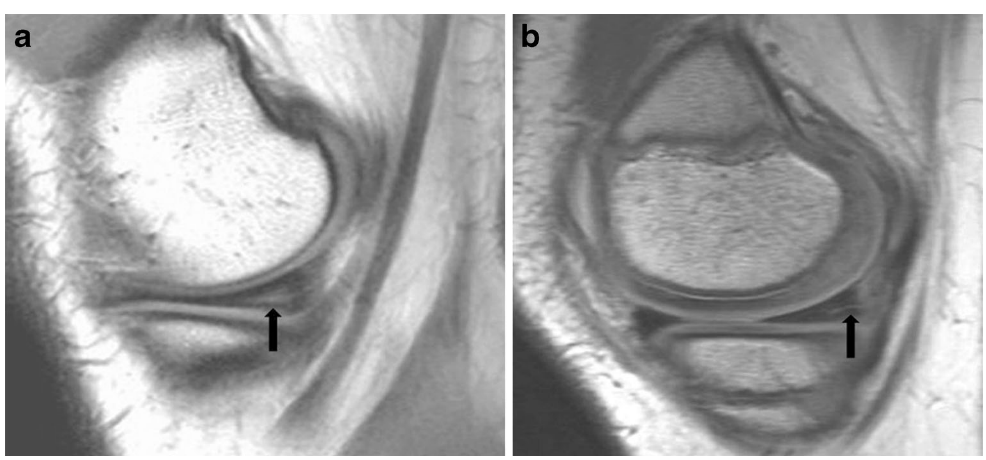
In general, two main etiologies exist for meniscal tears: tears occur when increased force is applied to the normal meniscus

Fig. 5 Grade 3 intrameniscal signal in a 16-year-old boy with a longitudinal meniscal tear. Coronal proton-density fat-suppressed MR image shows a longitudinal tear (*arrow*) of the medial meniscus with the linear high signal perpendicular to the tibial plateau and parallel to the arc/long axis of the meniscus involving the inferior articular surface

and when a normal force is applied on an abnormal meniscus, such as a discoid meniscus [10]. In children younger than 10 years a tear in a morphologically normal meniscus is rare [9]. In adolescents and young adults, because most menisci are normal, meniscal tears are associated with trauma. Meniscal tears in adults often belong in the second category and are related to degeneration [9, 17]. In the overall population, tears of the medial meniscus are reportedly more common [18]. However in patients younger than 30 years tears of the lateral meniscus are more common because of their association with sporting injuries and the association of meniscal tears with discoid menisci, which are typically lateral [9, 17].

Meniscal tears in children are commonly associated with concomitant injuries, most frequently ACL and medial collateral ligament (MCL) tears [36–38]. In a study by Stanitski et al. [39] including 70 pediatric patients ages 7–18 years with acute traumatic knee hemarthrosis, 46% demonstrated meniscal tears at arthroscopy. Although ACL injuries were the leading cause of hemarthrosis in this study, comprising 63% of the patients, 30% of the patients demonstrated isolated meniscal injuries [39]. Furthermore, 16% of patients demonstrated a combination of ACL and meniscal tear [39]. The

Fig. 4 Examples of intrameniscal signal grades. **a** Grade 1 intrameniscal signal in a 15-year-old girl. Sagittal proton-density MR image shows globular increased signal (*arrow*) in the posterior horn of the medial meniscus not touching the articular surface. **b** Grade 2 intrameniscal signal in a 6-year-old boy. Sagittal proton-density MR image shows linear intrameniscal signal (*arrow*) in the posterior horn of the medial meniscus not touching the articular surface



most frequent location of meniscal injury in children and young patients has been found to be different in patients with ACL tears and patients without ACL tears [8, 38]. In young athletes without ACL tears and nondiscoid meniscus, 70% of the meniscal tears occurred in the medial meniscus. Additionally, almost 80% were vertical tears; of those, 75% were in the posterior horn [8]. In a study by Samora et al. [38] the prevalence of lateral meniscal tear in patients with ACL tears was higher than both medial meniscal tears and combined tears. With a total of 124 skeletally immature patients who underwent arthroscopy, the lateral meniscus was involved exclusively in 41%, while the medial meniscus was involved exclusively in 13% of the cases; both menisci were involved in 15% of the cases [38]. The main meniscal tear pattern in this study was vertical and peripheral [38].

Children with chronic ACL tears also seem to show a different meniscal tear distribution. In a study analyzing pediatric patients with chronic ACL tears, meniscal injury equally involved both menisci with a frequency of 36% [37]. This increase in medial meniscal injury has also been demonstrated by Dumont et al. [40], who noted a higher rate of medial meniscal injury in pediatric patients with ACL tears treated after 150 days when compared to those treated before 150 days. Articular cartilage injury was also shown to have an association with meniscal and ACL injury in the same study [40]. Children with ACL tears and concurrent meniscal tears were more likely to have articular cartilage injury than those with ACL tears but no meniscal injury (Fig. 6) [40]. De Smet and Graf [41] showed that sensitivity for tears of the posterior horn of the lateral meniscus is decreased in the presence of an ACL tear, a potential pitfall in imaging.

Fig. 6 Articular cartilage damage secondary to an unrepaired meniscal and anterior cruciate ligament (ACL) tear in a 14-year-old boy. Coronal proton-density fat-suppressed MR image shows the markedly truncated and hyperintense lateral meniscus (*horizontal black arrow*) with a complex tear resulting in chondromalacia of the lateral compartment (*white vertical arrow*). Mild underlying bone marrow edema of the femoral and tibial condyles is present because of increased contact stress (*asterisks*). The torn ACL is not shown

MR imaging of the meniscus in children: technique

High-quality images are important in evaluating the menisci. It is not only important to optimize the protocol but also to use the proper coil. At Miami Children's Hospital, almost all knee MRIs are performed on a 3-tesla (3-T) magnet (Achieva; Philips Healthcare, Best, The Netherlands) with an 8-channel transmit receive knee coil, which is also available for the 1.5-T magnet (Intera; Philips). A 3-T magnet has the advantage of higher signal-to-noise and contrast-to-noise ratios [42]. The increased signal-to-noise ratio on 3-T magnets can be used either to decrease exam time, thereby decreasing chances of motion artifact and increasing patient through-put and comfort, critical in children, or to enhance image quality by increasing resolution [43].

Proton-density-weighted sequences are probably the most helpful to evaluate the meniscus. Because of their high signal-to-noise ratio, these images can be optimized to evaluate small structures such as the meniscus while also being able to evaluate the rest of the knee [44]. Fast spin-echo (FSE) imaging takes less time than conventional spin echo (CSE) imaging (potentially decreasing motion artifact, critical in children that are less cooperative). The use of short echo times (TE) of less than 20 msec theoretically can result in blurring, especially with long echo trains (ETL >5), small acquisition matrices and long inter-echo spacing. In the past there have been conflicting results in the literature as to whether fast spin-echo proton-density sequences are adequate for imaging the meniscus, with some reports in favor [45–47] and others against it [48–50]. To minimize blurring with FSE imaging, measures such as decreasing the echo train length (below 6), increasing the echo time (above 20 milliseconds) or increasing the bandwidth (over 200 Hz/pixel) to decrease inter-echo spacing can be applied [44]. With the use of high-performance gradients that allow shorter interecho spacing and the use of the second rather than the first echo as the effective echo time, the blurring is significantly minimized [45]. Without fat suppression, proton-density sequences provide anatomical images ideal for evaluating normal and abnormal menisci, ligaments and articular cartilage. Proton-density or T2-weighted images with fat saturation are sufficient to show soft-tissue edema and bone marrow edema [44]. Finally, axial images are also useful in evaluating the meniscus in combination with other imaging planes because they can help characterize abnormalities, especially in cases of complex tears (Fig. 7) [51, 52].

At our institution we use proton-density sequences with asymmetrical turbo spin echo (TSE), which is a strategy that employs asymmetrical profile ordering to fill k-space, achieving a reduction of both TSE-associated blurring and acquisition time. The use of asymmetrical turbo spin echo sequences provides independent selection of echo time, echo spacing and turbo factor, which allows the use of relatively short echo time (<30 ms) with a relatively large turbo factor, decreasing

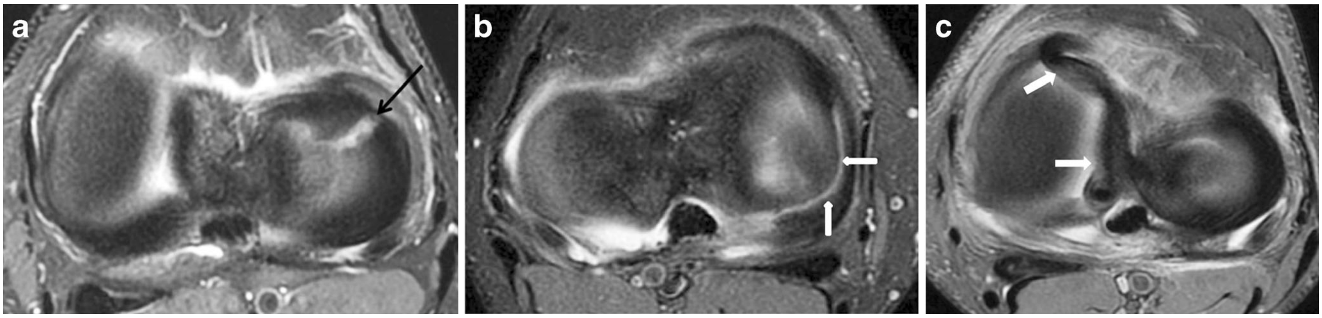


Fig. 7 Axial MRI of different meniscal tears. **a** Axial proton-density fat-suppressed image in a 13-year-old boy shows a radial tear at the anterior horn/body junction of the lateral meniscus extending from the free edge to the periphery of the meniscus (*black arrow*). **b** Axial proton-density fat-suppressed image in the same 16-year-old boy as in Fig. 5 depicts to better advantage the extent of the longitudinal tear (*arrows*) involving the posterior horn and body of the meniscus. **c** Axial proton-density fat-suppressed MR image in a 16-year-old boy shows a semicircular medial meniscal fragment flipped centrally (*arrows*) into the intercondylar notch, reflecting a bucket handle tear

acquisition time (Table 1 shows 1.5-T protocols; Table 2 shows 3-T protocols) [53, 54]. This sequence also allows good evaluation of the articular cartilage [55].

Types of meniscal tears

The morphology and nomenclature of the various types of meniscal tears in children is the same as in adults. Vertical tears are perpendicular to the tibial plateau and meet both the femoral and tibial articular surfaces [13, 17]. If a vertical tear extends to a free edge and is directed toward the center of the knee, it is a radial tear (Fig. 7). These can be complete if they involve the entire width of the meniscus, or they can be incomplete. Incomplete tears vary from low- to high-grade as more of the meniscus is involved as the tear propagates from the free edge of the meniscus to its periphery. Complete radial tears cause meniscal dysfunction by reducing potential hoop stress, allowing the edges of the meniscus to separate. On MRI signs of radial tears include the marching cleft sign, truncated triangle and ghost meniscus (Fig. 8) [17]. If the tear goes to the free edge at a different orientation, it is a parrot beak tear [13, 17].

Meniscal root tears are radial tears of the inner edge of the meniscus. The meniscal root, the portion of the meniscus that attaches to the tibia, is critical to meniscal function because it resists hoop stress, thereby preventing the outward displacement of the meniscus during axial loading. Meniscal root tears are serious injuries because they affect the functional competence of the meniscus and can lead to meniscal extrusion (Fig. 9) and eventually to early articular cartilage degeneration [32, 56, 57]. Root tears appear as a morphological distortion of the root, showing separation or detachment and abnormal intra-meniscal signal to the surface (Fig. 9) [58]. The posterior root of the medial meniscus is the most likely to undergo failure. Tears of the posterior root of the lateral meniscus are often, but not always, associated with ACL tears [58].

Vertical longitudinal tears are perpendicular to the tibial plateau but parallel to the arc of the C or U shape of the meniscus (Figs. 5 and 7). Horizontal or cleavage tears parallel to the tibial plateau dividing the meniscus into superior and inferior sections (Fig. 10) [17]. According to the International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) classification, these tears can be called horizontal tears even if they are oblique to the tibia [59]. Horizontal tears, although rare in children, usually occur in the setting of a discoid meniscus, as discussed in the discoid meniscus section.

In addition to in situ tears, several types of displaced meniscal tears are seen in adults and children. A flipped meniscal fragment occurs more commonly in the medial than the lateral meniscus and is associated with a longitudinal tear. The meniscal fragment is displaced centrally, posteriorly or anteriorly, while a portion of the fragment remains attached to the meniscus. If the fragment is flipped anteriorly, it may demonstrate the double anterior horn sign (Fig. 11). The bucket handle tear that usually occurs in the medial meniscus is an extensive longitudinal tear in which the inner fragment is displaced centrally into the intercondylar notch (Fig. 7). This is often demonstrated on MR as the double PCL sign (Fig. 12). Inferiorly displaced flap fragments usually occur with horizontal tears. The displaced flap fragment is flipped inferiorly into the inferior para-articular gutter, which can also occur with a radial tear of the body. A meniscal flap can completely separate from the meniscus and become a free meniscal fragment [13, 17].

Another injury worth mentioning is meniscocapsular separation. Meniscocapsular separation is a very peripheral tear in which there is a disruption of the attachment of the meniscus to the capsule. This is diagnosed on MRI by identifying increased distance, soft-tissue edema or fluid extending across the meniscocapsular junction (Fig. 13). The medial meniscus is more commonly affected than the lateral meniscus because of its more tightly adherent capsule [17].

Table 1 MR imaging protocols at 1.5 T using an 8-channel knee coil

Protocol	FOV (cm)	Slice thickness (mm)/gap size (mm)	Matrix	Bandwidth (Hz)	Sense factor	Fold-over direction	TSE factor	Time of echo (ms)	Flip angle (degrees)	Time of repetition (ms)	Fat suppression	NSA	Flow compensation
Sagittal T2-W FS	16	3/0.3	236×238	409.4	1	FH	17	67	90	3,723	SPAIR	3	Yes
Sagittal PD	14	3/0.3	256×248	485.2	1	FH	12	30	90	2,825	No	3	No
Axial PD FS	15	3/0.5	240×244	301.9	1.2	RL	8	30	90	2,829	SPIR	2	No
Coronal PD FS	15	4/0.4	264×254	308	1.3	RL	8	30	90	2,850	SPIR	2	No
Coronal T1-W	15	4/0.4	300×249	317.5	None	RL	3	13	90	620	No	2	No
Sagittal PD oblique	14	2/0.2	336×266	258.8	None	AP	8	30	90	2,888	No	3	No

AP anteroposterior, *FH* feet-head, *FOV* field of view, *FS* fat-saturated, *Hz* Hertz, *NSA* number of signal averages, *PD* proton density, *RL* right-left, *SPAIR* spectral attenuated inversion recovery, *SPIR* spectral presaturation with inversion recovery, *TSE* turbo spin echo

Table 2 Knee MR imaging protocols at 3 T using an 8-channel knee coil

Protocol	FOV (cm)	Slice thickness (mm)/gap size (mm)	Matrix	Bandwidth (Hz)	Sense factor	Fold-over direction	TSE factor	Time of echo (ms)	Flip angle (degrees)	Time of repetition (ms)	Fat suppression	NSA	Flow compensation
Sagittal T2-W FS	18	3/0	368×285	257.7	1.4	AP	13	69	90	4,394	SPAIR	2	Yes
Sagittal PD	15	3/0	376×279	183.6	1.5	AP	5	30	90	3,000	No	1	No
Axial PD FS	15	4/0	380×324	181.3	1.4	AP	5	30	90	2,875	SPIR	1	No
Coronal PD FS	14	3/1	384×284	189.9	1.4	RL	5	30	90	2,850	SPIR	1	No
Coronal T1-W	14	2.5/0.8	652×272	290.7	1.3	RL	6	20	90	633	No	2	No
Sagittal PD Oblique	14	2/0	312×378	196.1	2	AP	5	30	90	3,000	No	1	No

AP anteroposterior, *FOV* field of view, *FS* fat-saturated, *Hz* Hertz, *NSA* number of signal averages, *PD* proton density, *RL* right-left, *SPAIR* spectral attenuated inversion recovery, *SPIR* spectral presaturation with inversion recovery, *TSE* turbo spin echo

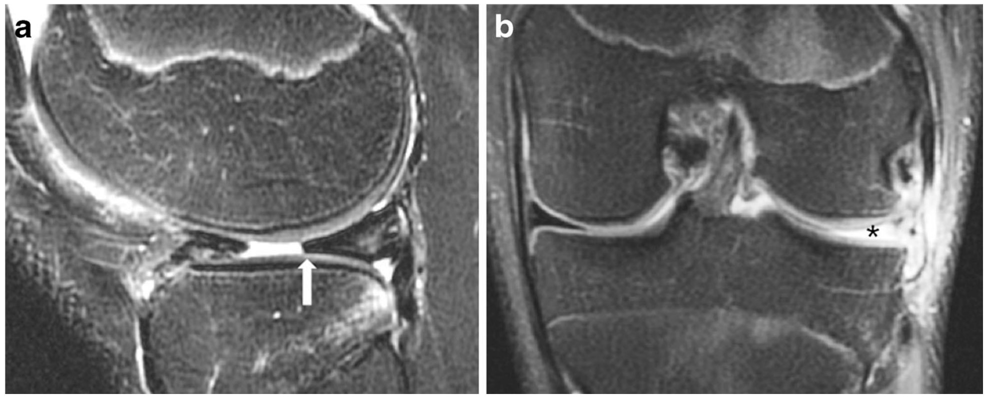


Fig. 8 Radial meniscal tear signs in a 13-year-old boy. **a** Sagittal proton-density fat-suppressed MR image shows the truncated triangle sign of the lateral meniscus (*arrow*). **b** The corresponding coronal MR image at the level of the meniscal body shows no lateral meniscus and is known as the ghost meniscal sign (*asterisk*)

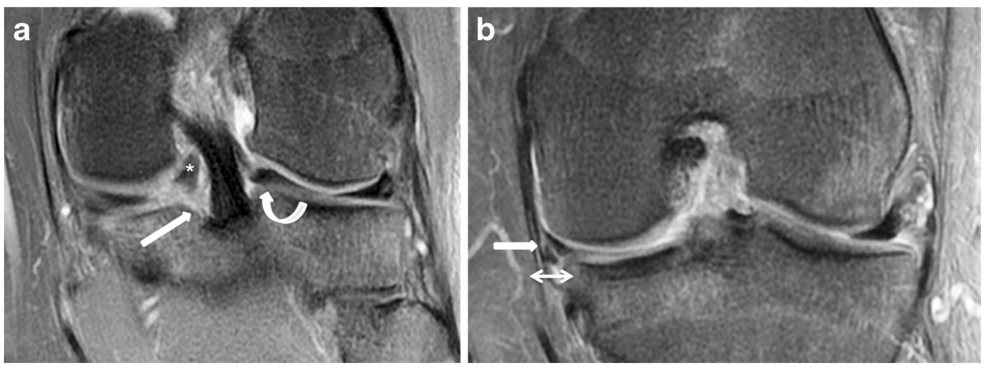


Fig. 9 Tear of the posterior root of the medial meniscus in a 16-year-old boy. **a** Coronal proton-density fat-suppressed MR image shows avulsion of the medial meniscal root attachment (*arrow*) with a flipped fragment (*asterisk*). Compare with the intact lateral meniscal root (*curved arrow*). **b** A more anterior image shows the medial meniscus extruded 3 mm from the tibial margin (*double-headed arrow*) with an oblique tear extending into the inferior articular surface (*arrow*)

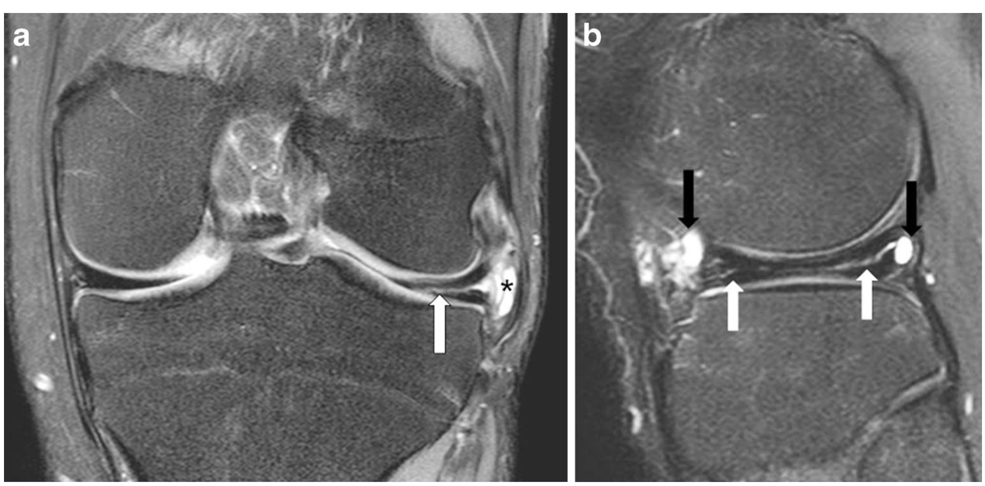


Fig. 10 MR imaging in a 16-year-old boy with a horizontal (cleavage) tear in an incomplete discoid lateral meniscus and three parameniscal cysts. **a** Coronal proton-density fat-suppressed image shows a horizontal linear high signal extending from the inferior articular surface of the thickened lateral meniscus (*arrow*) to the capsule, where there is a septated parameniscal cyst (*asterisk*). **b** Sagittal proton-density fat-suppressed image in the same boy shows the horizontal tear (*white arrows*) extending into the capsular meniscal margin anteriorly and posteriorly with two additional parameniscal cysts (*black arrows*)

Fig. 11 Double anterior horn sign of a flipped posterior horn. Sagittal proton-density MR image in a 16-year-old boy shows a large triangular meniscal fragment (*asterisk*) in contact with the anterior horn of the medial meniscus (*M*) and corresponding to the flipped posterior horn. The normal posterior horn cannot be seen (*arrow*)

Fig. 13 Meniscocapsular separation in a 15-year-old boy with an ACL tear. There is fluid (*asterisk*) between the posterior horn of the lateral meniscus (*M*) and the capsule consistent with meniscocapsular separation. Note the anterior translation of the tibia upon the femur secondary to the ACL tear (*double-headed black arrow*) and bone marrow contusions of the femoral notch and posterior lip of the tibial condyle (*white arrows*). *ACL* anterior cruciate ligament

Discoid meniscus

The discoid meniscus is a spectrum of meniscal disorders of shape and stability. Several hypotheses regarding its development exist, but the true etiology is unknown. One hypothesis suggests a congenital etiology with familial incidence; however, the normal meniscus is never discoid during its development [10, 60]. The histology and ultrastructure of the discoid meniscus is different from that of a normal meniscus. In the discoid meniscus, decreased collagen fibers and loss of normal collagen orientation are present. Intrameniscal mucoid degeneration is common, and mucoid material has been extracted [10, 60]. The true incidence and prevalence of discoid menisci are unknown because they can be asymptomatic. The incidence of discoid meniscus has been reported as 1.5–15.5% in the lateral meniscus (Fig. 14) and 0.1–0.3% in the medial meniscus (Fig. 15) [61, 62]. Bilaterality has been reported in up to 20% of cases [63–66]. Lateral discoid menisci have been also associated with osteochondritis dissecans (OCD) of the ipsilateral femoral condyle regardless of the state of the meniscus (i.e. torn or intact) [67, 68]. Individuals with a discoid meniscus can be asymptomatic [63]. However, some present with a click or pain, even in the absence of a tear. The snapping knee syndrome, in which a clunk is heard at the end of flexion, is usually related to an unstable meniscus variant, classically the Wrisberg type (discussed below) because of the lack of posterior capsular attachments [63, 69–71].

Fig. 12 Double posterior cruciate ligament sign in a bucket handle tear of the lateral meniscus. Sagittal proton-density fat-suppressed MR image of the same 16-year-old boy as in Fig. 7c shows a large curvilinear meniscal fragment (*arrows*) paralleling the posterior cruciate ligament (*asterisk*)

There are two main discoid meniscus classifications: Watanabe and Klingele. The classification system used by the radiologist should depend on the orthopedic surgeon's preference. The Watanabe classification is the most widely accepted and is followed at the authors' institution. It differentiates discoid menisci into three types as follows: type 1, complete; type 2, incomplete; and type 3, Wrisberg [72]. The complete type is disc-shaped, completely covers the lateral tibial plateau and has normal posterior attachments (Fig. 14). The incomplete type has a semilunar shape (Fig. 15) and normal posterior attachments but covers less than 80% of the lateral tibial plateau [10, 19]. The Wrisberg type can be normal or abnormal in morphology; however there are no posterior bony or capsular attachments, resulting in a hypermobile meniscus (Figs. 16 and 17). In some instances there are posterior capsular attachments with a

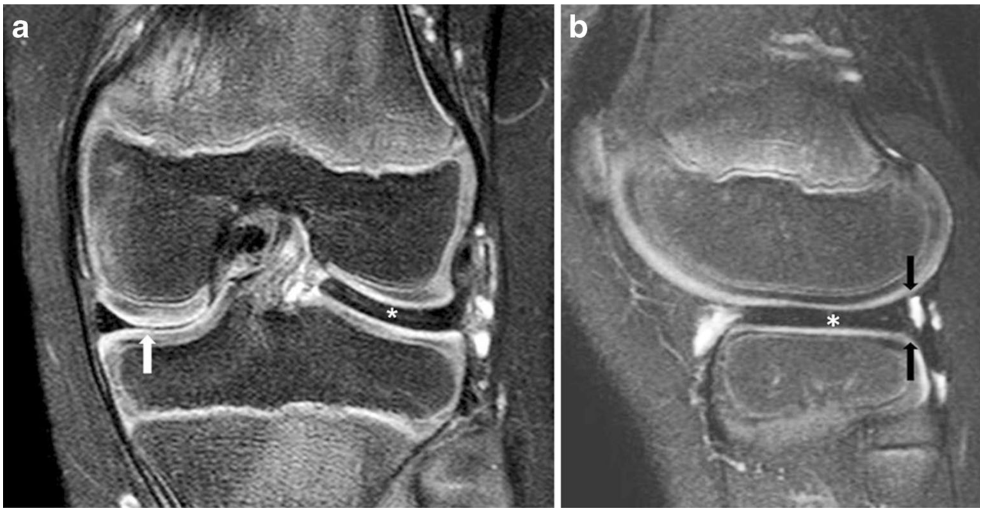


Fig. 14 Complete discoid lateral meniscus in a 12-year-old boy. **a** Coronal proton-density fat-suppressed MR image of the left knee shows a very thickened, disc-like lateral meniscus spanning the entire lateral compartment, representing a complete discoid meniscus (*asterisk*). The medial meniscus displays a normal central tapering (*arrow*). Similar findings were seen in the contralateral knee. **b** Sagittal proton-density MR image of the left knee shows the disc-like lateral meniscus (*asterisk*) with the normal posterior capsular attachments (*black arrows*)

prominent meniscofemoral ligament but no root attachment. This lack of stabilization allows the meniscus to subluxate anteriorly as flexion progresses, but then it reduces spontaneously on extension (Figs. 16 and 17) [69, 73, 74]. MRI plays an important role in children for making the diagnosis of discoid meniscus because the physical exam can be unreliable [75, 76].

The more recent Klingele classification separates the discoid meniscus into complete and incomplete types. It then classifies the two types as either stable or unstable. Instability is defined as “evidence of hypermobility and peripheral detachment of the remnant meniscus,” which is assessed by systematic probing after saucerization during arthroscopy. The unstable menisci of both complete and incomplete types are then further differentiated according to the presence of not only posterior but also anterior instability (Fig. 18) [72].

Fig. 15 Incomplete discoid medial and lateral menisci in a 12-year-old girl. Coronal proton-density fat-suppressed MR image shows markedly thickened medial and lateral menisci covering most of the tibial plateaus (*arrows*), indicating incomplete discoid menisci. There is increased intrasubstance signal in the lateral meniscus, likely representing mucoid degeneration (*asterisk*)

Discoid menisci are more susceptible to injury than normal menisci. It is thought that tears in discoid menisci are attributable to their abnormal shape and thickness, resulting in increased stress to the abnormal meniscal substance [60, 77, 78]. The discoid meniscus often has grade 1 or grade 2 signal abnormality without an identifiable tear on arthroscopy, probably representing mucoid degeneration (Fig. 15) [10, 60, 73, 79]. There is an increased incidence of tears in the discoid meniscus because of unusual biomechanical stresses [51]. Any tear pattern seen in a normal meniscus can occur in a discoid meniscus [60, 77]. Horizontal cleavage tears, otherwise rare in the non-discoid pediatric meniscus, are the most common tears in discoid menisci (Fig. 10) [10, 80]. Isolated lateral meniscal tears in children younger than 10 years should raise the suspicion of an underlying discoid meniscus, especially in the absence of significant trauma [10, 81, 82]. The Wrisberg-type discoid meniscus often demonstrates complex, degenerative tears in the thick posterior horn because of the increased to-and-fro motion to which the meniscus is exposed.

Meniscal cysts

Very little is reported in the pediatric literature regarding meniscal cysts [83, 84]. Most of this information has, instead, been published in the adult literature and does

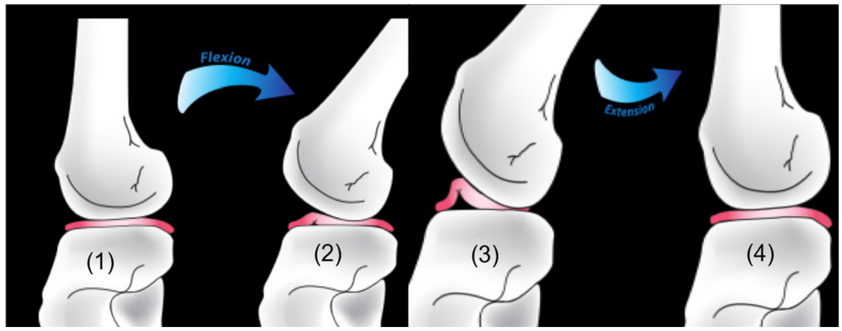


Fig. 16 Pictorial representation of the hypermobility associated with Wrisberg-type discoid meniscus. In neutral position (1) the meniscus is well located. As the patient flexes the knee (2, 3) the posterior horn of the hypermobile meniscus subluxates anteriorly and reduces with knee extension (4), causing the distinct clunk. Adapted with permission from Clin Sports Med 1990 Jul;9(3):695–706. Discoid Meniscus by Woods Gw and Whelan JM (Copyright Elsevier)

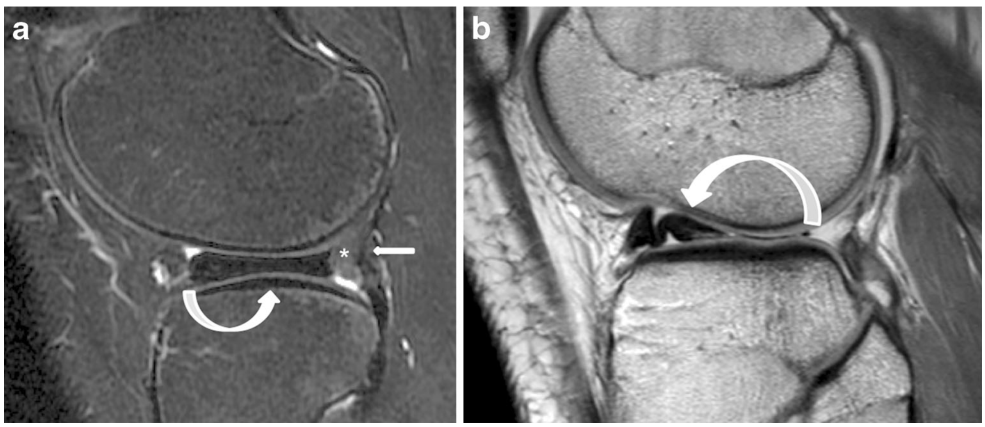


Fig. 17 MRI of the Wrisberg-type discoid lateral meniscus. **a** Sagittal T2-W fat-suppressed image in a 16-year-old girl with snapping knee syndrome shows a very thickened, disc-like lateral meniscus (*curved arrow*) with non-visualization of the popliteomeniscal fascicles and increased distance (*asterisk*) between the posterior meniscal margin and the capsule (*straight arrow*). **b** Sagittal proton-density MR image in a 14-year-old boy shows a crimped, anteriorly subluxated discoid lateral meniscus with slight knee flexion (*curved arrow*) indicating meniscal hypermobility

Fig. 18 Hypermobile meniscus caused by an anteriorly unstable lateral discoid meniscus in a 13-year-old boy. Sagittal proton-density fat-suppressed MR image shows a crimped, posteriorly subluxated lateral discoid meniscus (*curved arrow*) with a lack of anterior capsular attachments

not focus on children and adolescents [85]. The incidence of meniscal cysts in the general population varies from 4% to 8% [85, 86]. Meniscal cysts are classified as either intrameniscal or parameniscal. Intrameniscal cysts manifest as increased signal within an enlarged meniscus, can be linear or globular, and expand the meniscal contour with convex margins if they are not decompressed (Fig. 19). In cases of cyst decompression, the meniscus might have a more concave contour [87]. A parameniscal cyst, the most common type, is a focal fluid accumulation adjacent to the meniscus with a connection to the adjacent meniscus (Figs. 10 and 20). Concomitant occurrence of both types of meniscal cysts can be seen in the same meniscus [13]. Meniscal cysts can be asymptomatic or present with vague pain, decreased range of motion, and mechanical symptoms [87, 88]. Parameniscal cysts, in addition, may present as a palpable mass [87]. MRI-based studies, different from previous arthroscopic studies, have demonstrated that meniscal cysts are more common in the medial compartment [17, 85, 87–89].

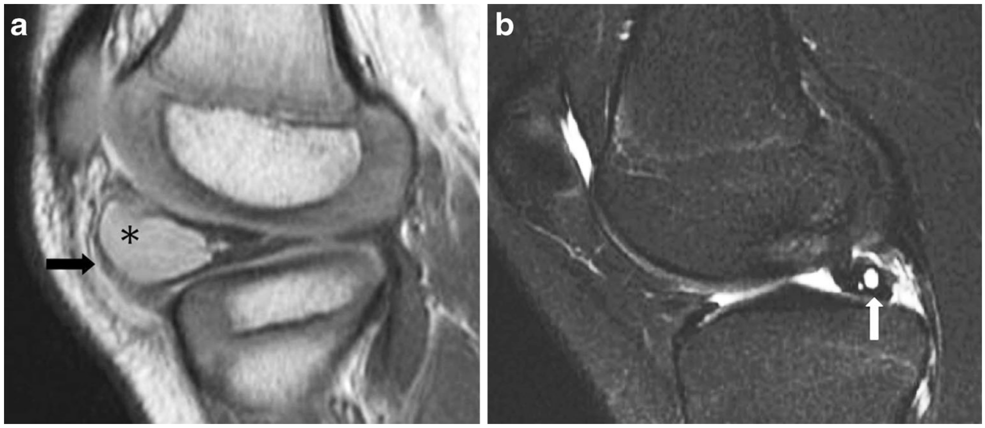


Fig. 19 Examples of intrameniscal cysts. **a** Sagittal proton-density MR image in a 9-year-old boy shows a large intrameniscal cyst as a globular intermediate signal structure (*asterisk*) expanding the anterior horn of the lateral meniscus and causing anterior convexity of the meniscal margin (*arrow*). **b** Sagittal proton-density fat-suppressed MR image in a 17-year-old boy shows a round fluid signal structure (*arrow*) in the substance of the posterior horn of the lateral meniscus consistent with an intrameniscal cyst. Note the convex superior meniscal surface

On MR imaging, both intrameniscal and parameniscal cysts appear as well-defined high T2 signal lesions of varying sizes and shapes, which can be unilocular (Fig. 19) or multilocular with septations (Figs. 10 and 20). Most intrameniscal cysts have T2 intermediate signal, while most parameniscal cysts have higher fluid signal. However, signal, shape and size are not definitive differentiating features. In fact, the most frequently seen intermediate T2 signal associated with intrameniscal cysts is similar to signal associated with intrasubstance degeneration [87].

There is still speculation regarding the etiology of meniscal cysts. One theory is that synovial fluid is absorbed through a tear in the meniscal articular surface and collects in the meniscus. However not every meniscal cyst is associated with a tear. Another theory is that the cyst arises from cystic meniscal degeneration without an associated tear [85, 87]. Despite these theories, the majority of meniscal cysts are associated with meniscal tears. This is supported in a study by Campbell et al. [85] showing that 108 of 109 meniscal cysts were associated with a tear.

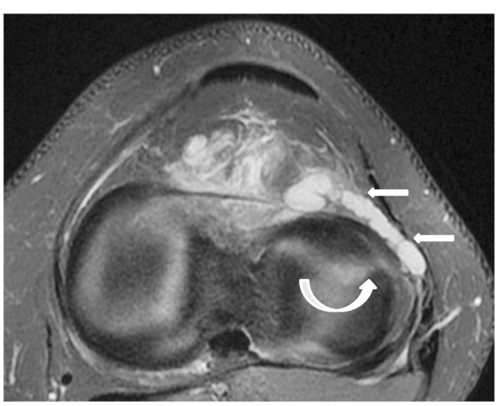


Fig. 20 Parameniscal cyst in a 14-year-old boy. Axial proton-density fat-suppressed MR image shows a large, lobulated parameniscal cyst (*straight arrows*) extending into the Hoffa fat pad in this boy with a radial lateral meniscal tear (*curved arrow*)

Prognostic indicators of meniscal tear repair

The location of a meniscal tear is important because it predicts the probability of successful healing. Peripheral tears are those within 3 mm of the capsular surface. These are most likely to heal because of good vascularity in that area. If needed, these tears are usually repaired with sutures or a tacking device. Tears near the red–white zone junction, between 3 mm and 5 mm from the capsule, have a variable likelihood of healing, and surgical management depends on the surgeon's judgment. In children, tears that occur in the red–white zone junction are given serious consideration for repair. Free-edge tears greater than 5 mm from the capsular surface are unlikely to heal because of poor vascularity, and they are usually debrided [90, 91]. Meniscocapsular separation may heal spontaneously because of the normally occurring peripheral vascularity [92].

Good prognostic factors after repair in non-discoid meniscus include younger age, lateral meniscal repair, peripheral tears, tear length less than 2.5 cm, concomitant ACL reconstruction, and surgical repair within 8 weeks of the injury [18]. If ACL and lateral meniscal tears are both present, the tear is usually located in the posterior horn/posterior root of the meniscus [93]. Furthermore, in a study analyzing the timing of pediatric and adolescent ACL surgical repair, Millett et al. [37] found that the incidence of medial meniscal tears increased with the interval between injury and surgery [94]. Medial meniscal tears were noted to be four times more common in patients with delayed ACL repair, which is repair 6 weeks after injury, than those with early ACL repair (Fig. 21) [37].

Fig. 21 Sagittal proton-density MR image in an 11-year-old male with an unrepaired chronic ACL tear shows a torn medial meniscus with antero–inferior dislocation of the anterior horn (*curved arrow*) and direct apposition of the femoral and tibial articular cartilage. There is posterior translation of the tibia (*double-headed arrow*) and severe muscle atrophy from decreased knee mobility. *ACL* anterior cruciate ligament

Partial meniscectomy can result in a significant increase in contact stresses and thus produce degenerative changes with more serious long-term implications in children than in adults because there is a longer period during which these changes can occur [36, 95]. Excision of a small bucket handle tear can increase the contact stress by 65% [10]. A total lateral meniscectomy has been reported to increase contact pressure as much as 335% [10]. In a study by Manzione et al. [95], 75% of children with partial or total meniscectomy were symptomatic by 5½ years after surgery, and 80% had degenerative changes on conventional radiography at follow-up examination on the affected side.

Discoid meniscus: role of arthroscopy and treatment

Discoid menisci can be asymptomatic so when they are incidentally found they do not require immediate treatment but it is prudent to observe them [66]. If the discoid meniscus is symptomatic (e.g., torn, unstable or both), surgical intervention is usually considered [96]. The increased thickness and width of the meniscus limits the ability to visualize the posterior aspect of the joint and the undersurface of the meniscus, where many tears often begin. MRI findings, therefore, should include the following: type of discoid meniscus, presence or absence of posterior attachments (i.e. meniscopopliteal fascicles), presence of associated degeneration, and any associated tears.

Arthroscopic treatment most commonly includes saucerization and debulking of the meniscus to restore the meniscal shape, followed by fixation to the capsule with sutures if there is meniscal instability upon probing [66]. Probing at arthroscopy is especially helpful in evaluating the unstable meniscus, including the Wrisberg variant, which can have a normal shape and MR appearance with abnormal attachments.

Not uncommonly discoid menisci will tear in the anterior horn of the meniscus. These tears can be treated by repairing the meniscus and suturing it to the anterior capsule [97]. These types of tears are seen in both incomplete and complete discoid menisci.

Meniscal cysts: role of arthroscopy and treatment

As discussed above, meniscal cysts are commonly associated with meniscal tears. Meniscal cysts are generally related to tears in the peripheral meniscus with subsequent cyst formation within or adjacent to the meniscus. Meniscal cysts are often treated during arthroscopy. They alternatively might be treated percutaneously or with open surgery [84, 98]. Surgical decision-making mainly depends on the location and size of the cyst, as well as the underlying meniscal pathology. If there is an associated articular surface meniscal tear, the meniscal tear and the cyst may be debrided from an intra-articular approach alone or by combining an intra-articular partial meniscectomy with a formal open cystectomy. If the meniscal cyst is not associated with an articular surface meniscal tear (in effect, it is contained within the substance of the meniscus), percutaneous extra-articular cyst aspiration can be performed to preserve the meniscus [75]. Alternatively, the cyst can be treated by perforating the meniscus, debriding the underlying cyst, and then re-approximating the meniscal surface [86].

Conclusion

Imaging is a central component in the evaluation of knee pathology. Meniscal injury in children is not uncommon; thus it is important for pediatric radiologists to be familiar with normal and abnormal appearances of the menisci on MRI. Normal meniscal signal in children can be different from that in adults until age 10–11 years, which can be a potential confounder to the unwary. Tears in children and adolescents tend to be more prevalent in the lateral meniscus. This is because of a higher incidence of sports-related injuries in younger patients compared to older patients and also the association of tears with discoid menisci. Discoid menisci can be symptomatic or asymptomatic and are predisposed to tears, especially horizontal tears. Meniscal tears in children younger than 10 years should raise suspicion for an underlying discoid meniscus. A precise description of meniscal tears is important for the surgeon because treatment is affected by the type, extent and location of the tear. Meniscal cysts of the intra- and parameniscal types also occur in children and are not necessarily associated with a meniscal tear. As the incidence of pediatric meniscal abnormality continues to increase, radiologists will continue to play an important role in their evaluation.

Conflicts of interest None

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