MRI of the Pediatric Knee

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OBJECTIVE. The purpose of this article is to describe findings on MRI in the evaluation of knee injury in pediatric patients.

CONCLUSION. Injury patterns in the pediatric knee overlap and differ from adults. Differences include open physes, changing mechanics, and differences in ligamentous support. Awareness of normal variants, common incidental findings, and normal evolution of bone marrow aid in the interpretation.

The knee is the joint most commonly imaged with MRI in the pediatric population. Common indications include assessment of internal derangement, pain, and further investigation of a radiographic abnormality. Although overlap between pediatric and adult pathology exists, particularly in the group of adolescents who have fused growth plates, there are significant differences in the types, prevalence, and underlying mechanism of injuries. The presence of open growth plates, which serve as a relative weak point, and inherent characteristics of the osseous structures predispose the pediatric population to a unique pattern of injury. Interpreters of pediatric knee MRI must be cognizant of these differences as well as normal variations, such as the normal evolution of bone marrow signal with age and incidental yet inconsequential findings unique to this group, such as fibrous cortical defects.

MRI is widely used for evaluation of the knee as well as other joints and provides many advantages. These include lack of ionizing radiation; multiplanar imaging capabilities; excellent resolution; and superior evaluation of the soft tissues, bone marrow, cartilage, muscle, ligaments, and tendons. MRI protocols vary by institution; however, in general the knee should be imaged in three orthogonal planes (axial, sagittal, and coronal), and at least one sequence should be obtained with fat saturation and one without. Our standard protocol for knee trauma or pain includes a sagittal proton density sequence without fat saturation and axial proton density images with fat saturation. Images are obtained at a 3-mm slice thickness with a 1-mm interslice gap. A 3D sagittal water-selective excitation sequence or 3D spoiled gradient-recalled echo with fat saturation sequence provides excellent assessment of the articular and physeal cartilage. Although not a focus of this article, imaging protocols for suspected tumor or infection at the knee will differ and include T1-weighted imaging and gadolinium-enhanced T1-weighted imaging with fat saturation. The purpose of this review article is to highlight the key MRI features encountered in pediatric knee trauma.

Menisci

One of the most commonly reported internal derangements in a skeletally immature knee is a meniscal injury; however, the incidence of meniscal tears is significantly less than compared with the adult population [1]. Although meniscal injuries are commonly associated with ligamentous injuries, meniscal injuries are more frequently reported than anterior cruciate ligament (ACL) injuries in a pediatric population. The medial meniscus is more frequently injured than the lateral meniscus and the posterior horn more commonly than the anterior horn. A strong correlation exists between MR evaluation of meniscal tears and surgical findings, with sensitivity of 80–85% and specificity of 88–100% reported in one study [1]. Meniscal signal characteristics have been widely accepted for use in the adult population and can also be used in the pediatric pop-
In adults, grade 2 meniscal signal has been attributed to myxoid degeneration; however, in the pediatric population, grade 2 signal may relate to persistent vasculature [4].

The criteria for diagnosis include visualization of the meniscal body on at least three or more 4- to 5-mm contiguous sagittal images, at least 2 mm or greater measurable height difference between the discoid and normal meniscus on the coronal plane, or greater than 12 mm in width [15].

A discoid meniscus has been associated with other anomalies, including a high fibular head, hypoplasia of the lateral tibial femoral condyle and tibial spine, and lateral joint space widening [15]. Meniscal cysts are also associated with discoid menisci; however, they are otherwise uncommonly seen in the pediatric population [2].

**Cruciate Ligaments**

ACL injuries are frequent in the adolescent population, more prevalent in girls and those of both sexes who are active in sports [16]. Reported contributing factors to female predominance include joint laxity, hormonal factors, limb alignment, configuration of the intercondylar notch, ligament size, and possibly earlier physeal fusion [17, 18]. The accuracy of MRI for detecting meniscal and ACL tears in adolescents is comparable with that of adults but is reportedly less accurate in patients before physeal closure [19].

Primary and secondary signs of ACL tears in children have been described and are similar to those seen in adults. Primary signs include fiber discontinuity, altered course, and abnormal signal of the ligament [20] (Fig. 3). Secondary signs include increased angle and abnormally vertical orientation of the PCL, anterior tibial displacement, uncovering of the posterior horn of the lateral meniscus, and kissing contusions of the lateral femoral condyle and medial tibial plateau [18, 20]. This pattern of bone marrow edema has been reported in skeletally immature patients even without an ACL tear, which may be secondary to increased laxity of the ACL in this population [21] in contrast with adult patients in whom ACL tears are consistently seen with this pattern of osseous contusion. Sensitivity of 95% and specificity of 88% in detecting ACL tears in children have been reported by Lee et al. [18] using both primary and secondary signs. Those authors found that primary findings were most reliable in diagnosing tears. In addition, this study discovered that meniscal tears were frequently associated with ACL injuries in children, more so than has previously reported in an adult population [18]. Fractures associated with ACL tears are avulsion of the lateral tibial rim at the insertion of the capsular ligament (Segond fracture), subchondral impaction fracture of the lateral femoral condyle, and avulsion of the tibial spine; however, these findings are not sensitive for diagnosis of ACL injuries [22].

Partial ACL tears are more common in the skeletally immature patient than the skeletally mature population [23]. This has been attributed to the relatively weaker bone at the ligament attachment site compared with the ligament itself. As the skeleton matures and growth plates fuse, the fused osseous structures are relatively stronger compared with the ligament, and therefore stresses on the knee result in a higher frequency of ligament tears compared with avulsions [23]. Differentiating partial from complete tears is critical because partial tears can be treated conservatively, whereas complete tears may need operative management. ACL reconstruction is a controversial topic because repair may lead to inadvertent injury to the femoral or tibial growth plates, resulting in premature physeal fusion and subsequent leg length discrepancies [24]. Physeal sparing procedures are typically performed in the younger population [24].

PCL injuries are uncommon in the pediatric population, but may occur with hyperextension injuries or with severe multiligamentous injury from knee dislocation. Hyperextension injuries of the knee may also result in avulsions of the posterior tibial plateau at the insertion site of the PCL without a tear of the PCL itself [25]. Similar to ACL tears, a PCL tear is diagnosed when there is disruption of fibers, increased signal intensity of the ligament, and redundancy of an avulsed ligament [26] (Fig. 4). Isolated PCL tears are rare and tears usually occur in the company of other ligamentous injuries [25]. Contusions of the anterior tibia and femur may be seen because of the hyperextension mechanism.

**Collateral Ligaments**

In the pediatric population, medial collateral ligament (MCL) and lateral collateral ligament (LCL) complex injuries are relatively uncommon compared with meniscal and ACL injuries. Similar to the adult population, collateral ligament injuries are seen in association with cruciate ligament and meniscal

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Pai and Strouse

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injuries [1, 3]. Injury to the MCL occurs secondary to valgus stress with the knee in a flexed position [27]. MCL and LCL injuries are classified as grades 1–3; grade 1 refers to microscopic injury; grade 2, to a partial tear; and grade 3, a complete tear [28]. On MRI, grade 1 is an intact ligament with variable amounts of surrounding edema, grade 2 is a ligament that is thickened or has abnormal signal with surrounding edema, and grade 3 is complete disruption of the fibers with surrounding edema (Fig. 5).

Bone and Cartilage

Before physeal fusion, the growth plates remain relatively weak and are a potential site of injury. Physeal injuries have been reported in up to 2.9% of pediatric knee MRI examinations [29]. Most physeal fractures are clinically suspected and radiographically evident; however, some physeal fractures can be subtle or radiographically occult, particularly those of the distal femur. MRI can be particularly helpful in these cases [29]. Evaluation of the physis should be part of the standard search pattern when interpreting knee MRI in the pediatric population. A Salter-Harris type II fracture is the most common type of physeal fracture and is also the most common fracture diagnosed on MRI [29]; linear abnormal signal intensity is identified in the metaphysis extending into the physis with associated widening of the growth plate (Fig. 6). Periosteal interruption or elevation can be seen with Salter-Harris II fractures, for which periosteal disruption is characteristically seen on the physeal fracture side of the growth plate as opposed to the metaphyseal side of the fracture [29]. Periosteal elevation may be seen on both sides. Uncommonly, avulsed periosteum may become entrapped within a physeal fracture [30].

Physeal widening because of stress injury has been reported in skeletally immature high-performance athletes [31]. These areas of physeal widening are thought to be secondary to repetitive stress and differ from Salter-Harris type I fractures, which result from acute injury [31]. With this type of chronic injury, a fracture line is not identified and the widening can be focal (Fig. 7).

Before physeal closure, avulsions of the tibial spine are not rare. In most cases, the ACL is intact but tibial spine avulsions may occur in association with ACL tears (Fig. 8). These patients can clinically present with an ACL-deficient knee, although the fibers remain intact [32]. The tibial spine is relatively weaker than the ACL in children and the configuration of the intercondylar notch has been implicated as a contributing factor to this injury, and those patients with a wider intercondylar notch may be predisposed to tibial avulsion fractures [33]. Tibial spine avulsion injuries may be radiographically subtle or occult and may be initially detected with MRI. Fortunately, because the ACL is usually intact, surgical repair of an avulsed tibial spine is usually simple and effective.

Chondral and osteochondral injuries were the most common lesions discovered in children undergoing MRI for evaluation of internal derangement of the knee in one study [34]. This study determined that chondral injuries were more frequently detected compared with meniscal and ACL injuries, and patterns varied depending on stage of physesal closure. Although the prevalence of chondral injuries did not change significantly with skeletal maturity, the pattern of chondral injury did. Before physeal closure, chondral injury of the femur was more commonly identified compared with patellar chondral injury after growth plate fusion. Subchondral bone marrow edema was a common associated finding [34]. Chondral injuries are considered significant because they may predispose to premature osteoarthritis and, if producing a loose fragment within the joint, may cause locking and pain [34]. Fat-suppressed spoiled gradient-echo MR sequences and sagittal water-selective excitation sequences are useful to assess cartilage.

Osteochondritis dissecans (OCD) is an acquired condition in which an osteochondral fragment partially or completely dislocates from the articular surface. Although this condition is likely posttraumatic in cause, other theories include repetitive mechanical stress, congenital factors, avascular necrosis, and even fat emboli [35]. The medial femoral condyle is the most affected (85% of cases); however, the inferocentral lateral femoral condyle, anterior lateral femoral condyle, femoral sulcus, and the patella can also be affected [36] (Fig. 9).

OCD may be diagnosed with radiography and seen as a focal lucency involving subchondral bone, often containing a central osseous fragment and variable degrees of surrounding sclerosis [37]. However, MRI is useful in assessing stability of the lesion, which has surgical implications because loose or displaced fragments require surgical management. Mesgarzadeh et al. [38] reported that MRI was 92% sensitive and 90% specific for separating stable from loose lesions. MR signs of instability have been described.

These signs are presence of a high-signal-intensity line along the fragment interface, disruption of the subchondral bone plate, and a 5-mm or larger fluid-filled cyst adjacent to the lesion [39]. Those with displaced fragments had the osseous defects filled with joint fluid [39]. Findings associated with good clinical outcome include stability of the lesion, small size of the OCD, and open growth plates [37]. Articular defect or cartilage fracture was associated with a poor outcome [37]. MRI criteria may have less specificity for instability in skeletally immature patients [40].

OCD must be differentiated from normal variants of ossification, most commonly seen along the posterior aspect of the lateral femoral condyle. Ossification defects in these areas with intact overlying cartilage and lack of bone marrow edema are features supportive of developmental variants [41] (Fig. 9).

Patella and Patellar Tendon

Traumatic patellar dislocation is a common acute knee injury in children, but it is often transient and occult and not suspected at the time of initial clinical or radiographic evaluation [42]. Typically, there is a complete, usually lateral, displacement of the patella out of the femoral groove and relocation, which is often spontaneous and not recognized. Indirect signs include hemarthrosis, contusion or osteochondral injury of the medial patellar facet and lateral femoral condyle, and injury to the medial patellar retinaculum [42] (Fig. 10). Predisposing factors include genu valgum, ligamentous laxity, shallow femoral trochlea, and abnormal morphology of the patellar facets.

Acute avulsion of the cartilage of the inferior patellar pole with an underlying bone fragment is termed “patellar sleeve fracture” and occurs most commonly in the 8- to 12-year-old population. Although radiographic and MR findings are similar and include joint effusion, avulsed osseous fragment, and patella alta, MRI can identify the true extent of injury, including the presence of a nondisplaced osteochondral fracture, the extent of soft-tissue injury, and the need for operative management [43, 44] (Fig. 11). Chronic avulsion injury of the inferior patellar pole is termed “Sinding-Larsen-Johansson syndrome.” MRI is also useful to determine the extent of findings, including fragmentation of the inferior patellar pole, infiltration of Hoffa fat-pad, and thickening of the proximal patellar tendon [45] (Fig. 11). Calcification or ossification of the tendon can also be identified.
Chronic avulsion or overuse injuries can also involve the tibial tubercle, termed “Osgood-Schlatter disease.” The tibial tubercle is an anterior extension of the tibial physis and is prone to injury because of its unique composition, which varies from other physes [43]. As the tibial tubercle matures, its susceptibility to injury from stresses incurred by the patellar tendon increases. Repetitive stress on the tibial tubercle by the patellar tendon causes inflammation at the tibial tubercle insertion site, reactive bone formation, bone marrow edema, proximal patellar tendon thickening, and soft-tissue swelling (Fig. 12). Although Osgood-Schlatter disease is a clinical diagnosis, MRI is useful in characterizing these changes, especially in the early stage of disease when only bone marrow edema may be present adjacent to the tibial tuberosity [46]. Osgood-Schlatter disease may predispose to avulsion fractures of the tibial tubercle, which also may be seen as an acute injury, most commonly in teenage boys involved in jumping sports [43]. When osseous irregularity is seen at this site in the absence of other findings and symptoms, irregularity of the ossification center must be considered as a normal variant.

Patellar variants are also encountered with imaging. Bipartite patella is a failure of fusion of a secondary ossification center of the patella, usually at the superolateral aspect of the patella [45]. This normal variant is usually asymptomatic; however, acute or chronic stress injuries may disrupt the synchondrosis between the accessory ossification center and patella, causing symptoms [47].

Incidental Findings and Normal Variations

Neoplasms and tumorlike conditions may present with pain, pathologic fracture, or be incidentally discovered during evaluation of the pediatric knee. Lesions include chondroblastomas, giant cell tumors, osteochondromas, osteoid osteomas, fibrous cortical defects or nonossifying fibromas, and cortical desmoids [48].

Fibrous cortical defects and nonossifying fibromas are well-defined cortically based lobulated lesions with sclerotic margins on radiography. Unless a pathologic or stress fracture is present, there will be no associated pain, edema, or periostitis. By definition, a lesion under 2 cm in size is a fibrous cortical defect and a lesion 2 cm or greater is a nonossifying fibroma (Fig. 13). The lesions are histologically identical. MRI and radiographic appearances are variable and relate to the stage of evolution. The lesions show T2 hypointensity early during development; however, as they involute, the T2 signal decreases or becomes undetectable [48] (Fig. 13). Involuting lesions are low signal on all sequences because of sclerosis. Lesions are well defined, lobular or unilocular, and cortically based. Edema is not identified with uncomplicated lesions, but edema may occasionally be seen with an associated stress fracture.

Avulsive cortical irregularities and so called cortical desmoids are commonly seen at the posteromedial distal femoral diaphysis (Fig. 13). These are thought to be secondary to chronic traction at the femoral insertion site of the medial head of the gastrocnemius or adductor magnus aponeurosis [49]. Cortical desmoids are focal well-defined sclerotic lesions along the cortical surface that are typically T1 hypointense and T2 hyperintense, with marginal sclerosis. A cortical desmoid disrupts the cortex from the outer surface and does not change in position over time [49]. In contrast, a fibrous cortical defect typically erodes the cortex from within the bone and tends to migrate proximally over time. Histologically, cortical desmoids and fibrous cortical defects are similar if not identical.

The normal evolution of bone marrow must also be considered when interpreting any MRI. The signal of bone marrow reflects topology of the medullary cavity and is heterogeneous. The normal physeal plate is a relative point of weakness before physeal fusion; changing mechanics; and differences in ligamentous support. When differences in pathology, disease prevalence, and mechanism of injury are acknowledged, a more accurate interpretation of the MRI findings can be rendered in the pediatric population. In addition, awareness and understanding of normal variants and normal evolution of bone marrow signal may aid in the interpretation of MRI and help avoid unnecessary further workup or intervention.

Pai and Strouse

References

20. Brandser EA, Riley MA, Berbaum KS, El-Khoury GY, Bennett DL. MR imaging of anterior cruciate ligament injury: independent value of primary and
MRI of the Pediatric Knee


Fig. 1—17-year-old soccer player who twisted his knee. Sagittal proton density–weighted image through knee at level of posterior cruciate ligament (PCL) shows abnormal tissue (arrow) just deep in relation to normal PCL (arrowhead). This is example of double PCL sign and signifies bucket-handle tear of medial meniscus with flipped fragment.

Fig. 2—8-year-old boy with knee pain and no history of trauma. Coronal proton density–weighted image through knee shows discoid lateral meniscus with abnormal intrameniscal signal, compatible with degeneration (arrow).
Fig. 3—9-year-old boy who injured his knee while playing football. Sagittal proton density–weighted image through knee shows fiber disruption and abnormal signal of anterior cruciate ligament, compatible with complete tear (arrow).

Fig. 4—14-year-old girl who injured her knee while jumping on trampoline. Axial proton density–weighted image with fat saturation through knee shows amorphous appearance and edema of posterior cruciate ligament, compatible with tear (arrow). Notice normal configuration and signal of anterior cruciate ligament located anteriorly (arrowhead).

Fig. 5—Collateral ligament injuries.
A, 13-year-old boy who was injured playing football. Coronal proton density–weighted image through knee shows abnormal fluid adjacent to intact medial collateral ligament (MCL), compatible with grade 1 injury (arrow).
B, 13-year-old boy who was struck by car. Coronal proton density–weighted image through knee shows disruption of lateral collateral ligament complex (arrow), with extensive surrounding edema. Findings are compatible with grade 3 injury.
C, 17-year-old football player who sustained direct trauma to lateral aspect of his knee. Coronal proton density–weighted image through knee shows complete tear of MCL, with wavy appearance of ligament distally and surrounding fluid (arrow). Associated anterior cruciate ligament tear was identified (arrowhead). This patient also had bone marrow edema of lateral femoral condyle.
Fig. 6—17-year-old soccer player who was kicked during practice. Coronal proton density–weighted image through knee with fat saturation shows linear signal intensity extending from distal femoral metaphysis through medial physis, compatible with Salter-Harris type II fracture (arrow). Note adjacent bone marrow edema and disruption of periosteum (arrowhead). Joint effusion is also seen.

Fig. 7—12-year-old soccer player with knee pain. 
A, Coronal proton density–weighted image through knee shows widening and indistinct appearance of medial distal femoral physis, compatible with stress injury of growth plate (arrow).
B, Coronal proton density–weighted image with fat saturation through knee shows similar findings, with mild edema along margins of physis (arrow).

Fig. 8—13-year-old boy who felt his knee “give out” while being tackled by another player during football practice.
A, Sagittal proton density–weighted image through knee at level of anterior cruciate ligament (ACL) shows avulsion fracture of tibial spine with bone marrow edema (long arrow). The ACL (arrowhead) is intact, as it often is with this fracture. Fluid–fluid level of hemarthrosis is also noted (short arrows).
B, Coronal proton density–weighted image with fat saturation through knee shows bone marrow edema of avulsed tibial spine (arrow).

Fig. 9—Osteochondritis dissecans (OCD) and normal variant mimicking OCD.
A, Sagittal proton density–weighted image of knee of 15-year-old girl shows abnormal subchondral marrow signal involving weightbearing aspect of medial femoral condyle with overlying cartilage irregularity, compatible with OCD (arrow). Joint effusion is also present.
B, Contrast-enhanced sagittal proton density–weighted image through knee of 9-year-old boy shows hypointense signal alterations within posterior aspect of medial femoral condyle with normal appearing overlying cartilage (arrow). This is example of normal developmental variant.
Fig. 10—14-year-old football player tackled during practice who presented with anterior knee pain. A, Axial proton density–weighted image with fat saturation through level of patella shows contusions of lateral femoral condyle and medial patellar facet, edema and injury to medial patellar retinaculum, and osteochondral fragment (arrow) within lateral joint recess, compatible with transient patellar dislocation. B, Sagittal water-selective excitation sequence through knee shows osteochondral defect (donor site) from inferior patella (arrow).

Fig. 11—Inferior patellar pole. A, Sagittal proton density–weighted image through knee of 12-year-old basketball player shows fracture of inferior patellar pole, compatible with patellar sleeve injury (arrow). B, Coronal proton density–weighted image with fat saturation through knee of another 12-year-old basketball player shows fragmentation of inferior patellar pole (arrow) with associated bone marrow edema and mild thickening of proximal patellar tendon. Findings are compatible with Sinding-Larsen-Johansson syndrome and traction apophysitis at level of proximal patellar tendon.

Fig. 12—11-year-old boy with knee pain. A, Sagittal proton density–weighted image through knee shows fragmentation of tibial tubercle, with overlying soft-tissue swelling and thickening and abnormally increased signal of distal patellar tendon (arrow). B, Axial proton density–weighted image with fat saturation through level of distal patellar tendon shows thickening and abnormally increased signal (arrow). Findings are compatible with Osgood-Schlatter disease.
Fig. 13—Fibrous cortical defect and cortical desmoid. 

A, Coronal proton density–weighted image with fat saturation in 15-year-old boy shows cortically based lobulated heterogeneously hyperintense lesion along distal femoral metaphysis measuring less than 2 cm, compatible with fibrous cortical defect (arrow).

B, Axial proton density–weighted image with fat saturation of 13-year-old girl shows cortically based lobulated hyperintense lesion involving posteromedial distal femoral metaphysis near adductor magnus aponeurosis, compatible with cortical desmoid (arrow).