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Annals of Sports Medicine and Research

Review Article

Anterior Cruciate Ligament Injuries: MR Imaging Diagnosis with Surgical Implications

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Submitted: 30 June 2023
Accepted: 31 July 2023
Published: 31 July 2023
ISSN: 2379-0571

Keywords
- Anterior cruciate ligament
- Ligament injury
- Magnetic resonance imaging

Abstract

The anterior cruciate ligament (ACL) is an important stabilizing structure of the knee, preventing anterior translation and internal rotation of the tibia in relation to the femur. The disruption of ACL may result in impairment in function and the early onset of joint degeneration. Therefore, the accurate and timely diagnosis of ACL injuries is important. MR imaging is an accurate and important tool in diagnosing ACL injuries, and various primary and secondary signs of ACL injury have been reported. It is important to recognize the characteristic imaging findings on MRI and correlate these findings with the mechanism of trauma. ACL injuries may be associated with injuries to other supporting structures of the knee, such as menisci, collateral ligaments, the anterolateral ligament, and structures of the posterolateral corner. The presence of associated findings may alter the treatment plan, and therefore is important to diagnose them on imaging.

ABBREVIATIONS

ACL: Anterior Cruciate Ligament; AM: Anteromedial; PL: Posterolateral; MRI: Magnetic Resonance Imaging

INTRODUCTION

The anterior cruciate ligament (ACL) is an important stabilizing structure of the knee, preventing anterior translation and internal rotation of the tibia in relation to the femur. The disruption of ACL may result in impairment in function and the early onset of degenerative joint disease. Therefore, the accurate and timely diagnosis of ACL injuries is important. MRI is the most accurate modality to evaluate the ACL. In this review, we will discuss the anatomy of the ACL, the risk factors and mechanism of ACL injury, MR imaging findings of ACL injury along with surgical implications.

ANATOMY

The ACL is a ligamentous structure composed of dense connective tissue with type I collagen fibers, interspersed fibroblasts, and matrix components. Type I collagen fibrils are oriented parallel to the longitudinal axis of the ligament and contribute to its tensile strength [1]. Blood supply to the ACL is primarily from the middle genicular artery that branches from the popliteal artery, with additional secondary supply from the inferomedial and inferolateral genicular arteries via the anterior fat pad [2]. Proprioceptive mechanoreceptors are found in the ACL, which is supplied by the tibial nerve [3].

The ACL originates from the posteromedial surface of the lateral femoral condyle and runs an oblique course to insert on the tibia at the anterior intercondylar area, just anterior and lateral to the medial tibial spine. The cross-sectional area of the ACL varies over the length of the ligament; it is smallest at the mid-substance and up to 3.5 times larger at the origin and insertion sites [4,5]. There are two distinct functional bundles of the ACL: the anteromedial (AM) bundle and the posterolateral (PL) bundle, which are named based on the relative insertion sites on the tibia [4,6]. The AM bundle originates at the anterior and proximal portion of the femoral attachment and insert at the anteromedial portion of the tibial footprint, whereas the PL bundle start at the posterior and distal portion of the femoral attachment and inserts on the posterolateral portion of the tibial insertion [7]. The average length of the AM bundle has been reported to be 28 to 38 mm, which is longer than the PL bundle, which averages 17.8 mm [4,8,9]. Due to the difference in length and point of insertion, the tension of the two bundles differ during knee flexion and extension: the AM bundle is taut when the knee is in ≥60° of flexion, whereas PL bundle is tight with knee extension, internal and external rotation [10], contributing to the different function of the two bundles. It is thought that the

AM bundle contributes mostly to resisting anterior translation of the tibia whereas the PL bundle has a role in rotational stability [11]. An additional intermediate bundle has been occasionally noted between the two bundles [7,12].

MECHANISM OF INJURY

The majority of ACL injuries are non-contact injuries from various movements in sports-related activities; pivoting, cutting, jumping, acceleration and deceleration [13,14]. It is known that in about three fourths of the cases, the ACL is injured by a non-contact pivot shift mechanism, where the tibia translates anteriorly while the knee is in slight flexion and valgus [15,16]. The bone bruise patterns noted on MRI also suggest that a large anterior translation of the tibia relative to the femur, a small knee flexion angle, and knee valgus are important components in ACL injuries [16-18]. The ACL is the main restraint against anterior translation of the tibia accounting for 90% of the resistance to anteriorly directed loads [19]. Therefore, anterior translation of the tibia is thought to be the primary mechanism of ACL injury [16]. The ACL is at maximum strain when the knee is in near full extension with a small flexion angle, increasing the risk of injury [20,21]. Internal rotation of the tibia is also known to increased ACL load and may contribute to ACL tears [16,22,23].

Less frequently, the ACL may be injured by a contact-type mechanism resulting from a high-energy trauma producing extensive valgus stress or hyperextension of the knee joint. The majority of contact injuries occur form a lateral-sided collision to the knee leading to valgus stress and lateral compartment compression [24].

RISK FACTORS

Anatomic risk factors may contribute to ACL injury, including knee geometry, ACL volume, and generalized joint laxity [25]. It has been reported that a narrow intercondylar notch is associated with increased risk of ACL injury [26-29]. Studies have also shown that bony tibial geometry may contribute to ACL injury: a larger posterior-inferior-directed lateral tibial plateau slope and shallower medial tibial plateau depth can predispose to ACL injury (30). Features of the ACL itself may also predispose the ligament to injury; a decreased width, decreased volume, and increased length of the ligament have been reported to be associated with ACL injury [31,32].

Physiologic factors may also increase the risk of ACL injury. A body mass index that is higher than average is a risk factor for ACL injury [29,33]. Sex of the patient has been reported to influence ACL injury, with conflicting results. Some studies have shown that males have a higher absolute incidence of ACL injury [34-36]. However, when normalized with exposure to sports activity, females have a higher ACL injury rate in most sports, including basketball, soccer, softball/baseball, handball, and lacrosse [37-39]. Neuromuscular factors such as hamstring-quadriceps imbalance may predispose individuals to an increased risk for ACL injury [40].

MR IMAGING

MR Imaging is the modality of choice in diagnosing ACL tear with a reported sensitivity, and specificity range of 63.6-100% [41-43] and 68.4-100% [43-46], respectively. A meta-analysis by Li et al. [47], reported a pooled sensitivity of 87% (95% CI, 84–90%) and specificity of 90% (95% CI, 88–92%). MRI has a role in confirming the clinical diagnosis of ACL injury and identifying associated injuries of the meniscus, cartilage and collateral ligament.

IMAGING PROTOCOL

MRI is performed on a 1.5T or 3.0T MR scanner, using a dedicated knee coil. Although imaging protocols vary across institutions, a combination of short echo time pulse sequences and fat-suppressed fluid-sensitive pulse sequences in all three orthogonal planes are helpful in assessing the ACL.

The imaging evaluation of the ACL starts in the sagittal plane. However, the ACL may be incompletely visualized, and evaluation may be hindered by partial volume averaging in the sagittal plane. The addition of coronal and axial plane images increases the sensitivity, specificity, and diagnostic confidence in detecting ACL tears [48,49]. Oblique sagittal and oblique coronal planes can also help improve the diagnostic accuracy of MRI in assessing ACL tears [50-53]. A sagittal plane angled at 80 degrees from a reference line through the intercondylar joint space has been reported to be helpful in visualizing the ACL in its full length [51].

MRI FINDINGS OF NORMAL ACL

The normal ACL appears as an obliquely oriented, taut, continuous fibrous band extending from the posteromedial aspect of the lateral femoral condyle to the anterior aspect of the tibial eminence (Figure 1A). The slope of the ACL should be parallel or near parallel to the roof of the intercondylar notch (Blumensaat line). The proximal portion of the ACL exhibits an oval-shape in cross-section with uniform low-signal intensity on T1-, intermediate- and T2-weighted pulse sequences. As the ACL approaches the tibial insertion, the fibers are flared, and the signal intensity is increased exhibiting a striated appearance with alternating bands of low and intermediate signal intensity. The AM and PL bundles can be distinguished with intermediate signal intensity interposed between the two bundles (Figure 1B).

MRI FINDINGS OF ACL INJURY

MR findings of ACL injury can be divided into primary signs related to the changes of the ACL itself, and secondary signs related to changes in the surrounding structures. The most reliable primary sign of acute ACL tear is the discontinuity of the ligament fibers, and the failure of the ACL fascicles to parallel the Blumensaat line on sagittal image [54] (Figure 2A). The ligament fibers may be edematous and hemorrhagic resulting in diffuse enlargement and cloud-like hyperintense T2 signal in the acute to subacute phase [55] (Figure 2B). The proximal stump of the torn ACL is usually oriented more vertically, and the

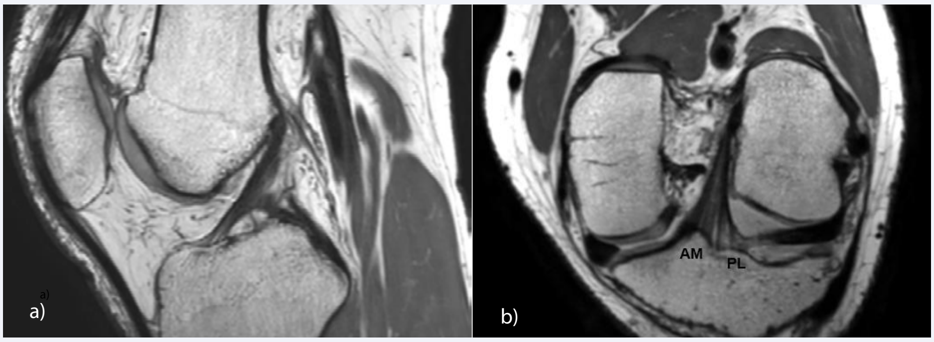

Figure 1 Imaging appearance of normal ACL. (A) The normal ACL appears taut with a slope slightly more vertical to the Blumensaat line. The ACL exhibits a striated appearance with alternating bands of low and intermediate signal intensity. (B) Oblique coronal image that parallels the course of the ACL show the anteromedial and posterolateral bundle, which are named based on the relative insertion sites on the tibia.

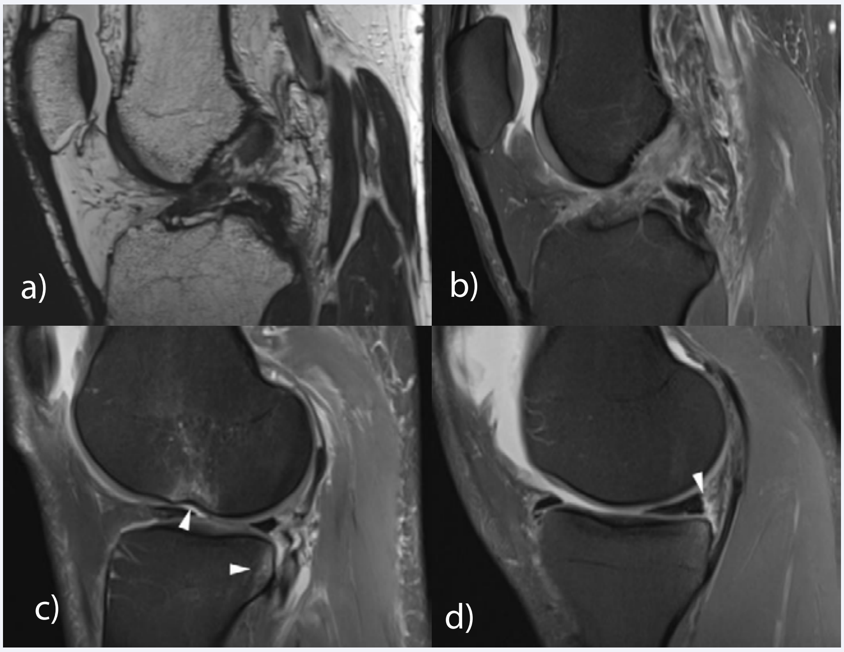

Figure 2 Primary and secondary signs of ACL tear. (A) Sagittal T2-weighted image shows discontinuity of the ACL at the mid-substance indicating a complete tear. (B) Sagittal fat-suppressed proton density-weighted shows diffuse enlargement and cloud-like hyperintense signal intensity of the ligament, resulting from edema and hemorrhagic change of the ligament. (c) Sagittal image through the lateral compartment shows kissing bone contusion involving the posterior aspect of the lateral tibial plateau and the mid portion of the lateral femoral condyle at the sulcus terminalis, which indicates a pivot shift injury. A slight depression fracture at the sulcus terminalis of the lateral femoral condyle is noted ("deep notch sign") (D) A thin fluid signal is interposed between the posterior horn of the medial meniscus and the posteromedial capsule, leading to the diagnosis of meniscal ramp lesion associated with ACL tear.

distal stump more horizontally compared with the Blumensaat line. Nonvisualization of the ACL fibers is a common and specific finding of chronic complete tear of the ACL, resulting in an empty intercondylar notch [56, 57]. Another common finding of chronic ACL injury is a thin residual fiber demonstrating an abnormal slop. Occasionally, a chronic tear may be mistaken for an intact ligament, due to the fibrous scar that bridges the proximal and distal stumps giving the ACL a continuous appearance [55].

Various secondary signs may aid the diagnosis of ACL tears; anterior translation of the tibia, uncovering of the posterior horn of the lateral meniscus, buckling of the PCL, characteristic bone contusion patterns, and Segond fracture. Anterior translation of the tibia with reference to the femur is a helpful finding in diagnosing complete tears of the ACL [58] (Figure 3). The degree of translation can be measured in the lateral compartment on sagittal images, as the distance between the posterior margin of the proximal tibia and the posterior margin of the lateral femoral condyle. Translation of 5mm or greater has been reported to show a sensitivity of 86% and specificity of 99% for ACL tear [59]. Anterior translation may lead to uncovering of the posterior horn of the lateral meniscus, and buckling of the PCL [60].

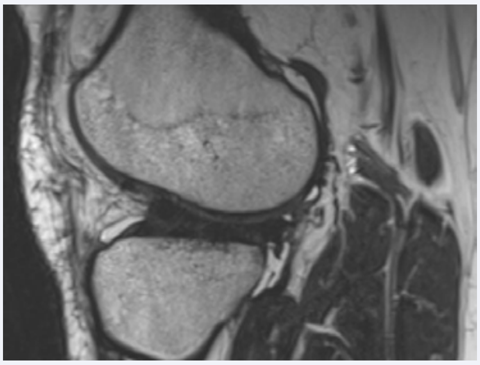

Figure 3 Secondary sign of ACL tear. The tibia is anteriorly translated with reference to the lateral femoral condyle, leading to uncovering of the posterior horn of the lateral meniscus.

The pattern of bone contusions depends on the mechanism of injury and can be helpful in diagnosing associated injuries of the meniscus and other ligamentous structures. The most common bone contusion pattern is the kissing bone contusion involving the posterior aspect of the lateral tibial plateau and the mid portion of the lateral femoral condyle at the sulcus terminalis, which is associated with pivot shift injury [16] (Figure 2C). Pivot shift reciprocating bone contusions indicate the impaction of the femoral condyle on the posterior aspect of the tibial plateau during anterior translation. Less commonly, bone contusions can be noted along the posterior aspect of the medial tibial plateau and the medial femoral condyle. Contusions of the medial compartment are thought to result from a contrecoup injury at the point of reduction [17]. Stronger compressive forces at the time of injury may cause cortical depression fractures in the tibia and femur. A depression fracture at the sulcus terminalis of the lateral femoral condyle is termed "deep notch sign" and is known as an indirect sign of acute ACL tear [61] (Figure 2C). With a depth cut-off of 1.5mm, the deep notch sign has a specificity of 100%, sensitivity of 15.4%, positive and negative predictive value of 100% and 49.1% respectively [62]. The deep notch sign was originally described on radiograph but can also be noted on MRI [63].

A Segond fracture is an avulsion fractures located at the lateral rim of the tibia, pathognomonic for an ACL tear [64,65] (Figure 4). Segond fractures occur from forced internal rotation and varus loading of the tibia relative to the femur [64,66]. They have been attributed to various structures; the mid-third lateral capsular ligament, the iliotibial band, the anterior arm of the biceps femoris tendon, the anterolateral ligament, and the anterolateral complex consisting of the ITB and anterolateral capsule [66-72]. Segond fracture has a reported prevalence of 2.4% to 29% in patients with ACL tears [64,65,73,74]. The healing of a Segond fracture may lead to a characteristic bone excrescence at the lateral aspect of the proximal tibia ("Bosch-Bock bump") [73] (Figure 4D).

PARTIAL TEARS OF THE ACL

The diagnosis of partial tears of the ACL may be more challenging than complete tears; the sensitivity and specificity of MRI in diagnosing partial tears have been reported to be 40-75% and 62-89%, respectively [75]. The partially torn ACL shows sagging of the ligament contour with some continuous fibers, and hyperintensity on fluid-sensitive sequences (Figure 5). The loss of continuity in more than 50% of the ACL fibers indicates a high-grade partial tear, whereas less than 50% of fibers torn is a low-grade partial tear. Partial tears of the ACL may be difficult to differentiate from complete ACL tears, mucoid degeneration of the ACL or even a normal ACL, due to the overlapping imaging features [76].

IMAGING PITFALLS

Potential pitfalls in diagnosing ACL tears on MR imaging include partial volume averaging, fibrosis following ACL injury, mucoid degeneration, and ganglion cyst formation. The distal fibers of the ACL is separated by thin fat planes, hence the striated appearance on MRI. This normal striation should not be mistaken for a partial tear. Partial volume averaging can occur between the ACL and other structures in the intercondylar notch, including synovial fluid, fat, and bone. This may resulting in an increased intrasubstance signal intensity or incomplete visualization of the contiguous fibers along the entire course of the ACL, which may be erroneously interpreted as ACL tear [77]. In order to avoid erroneous interpretation, the ACL should be evaluated not only on sagittal image but also on axial and coronal images. The ACL may undergo fibrotic scarring following complete tear which may be mistaken for an intact or partially torn ACL in the chronic stage [55]. The residual ACL stump may adhere to adjacent structures such as the posterior cruciate ligament or the femoral notch.

The ACL can undergo mucoid degeneration or intrasubstance ganglion cyst formation mimicking tear [78]. Mucoid degeneration of the ACL manifests as a thickened and ill-defined ligament with increased signal intensity interspersed among visible intact fibers on MRI ("celery stalk" sign) [79], which results from the deposition of amorphous mucoid matrix along the fibers of the ACL (Figure 6A). Ganglion cysts appear as a fusiform, lobulated or multilobulated lesion with fluid-equivalent signal intensity on all pulse sequences [80]. Ganglion cysts are typically located along

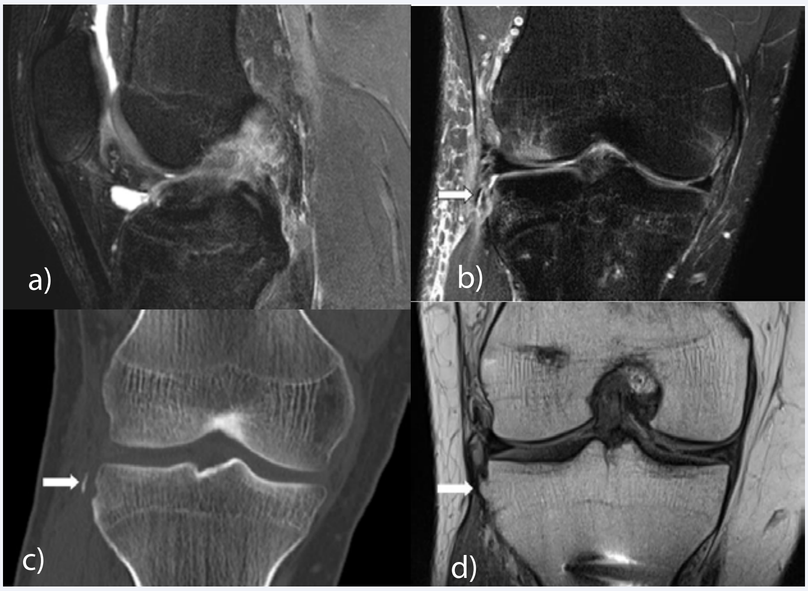

Figure 4 Segond fracture and Bosch-Bock bump. (A) Sagittal fat-suppressed T2-weighted image shows a complete tear of the ACL. (B) On coronal fat-suppressed T2-weighted image, a small avulsed bone fragment (white arrow) is noted at the lateral rim of the tibia (Segond fracture), which is a finding pathognomonic for an ACL tear. (C) Corresponding CT images clearly depicts the Segond fracture. (D) The patient underwent ACL reconstruction surgery and on postoperative follow-up MRI taken 2 years after the injury, the Segond fracture has healed, creating a characteristic bone excrescence at the lateral aspect of the proximal tibia ("Bosch-Bock bump").

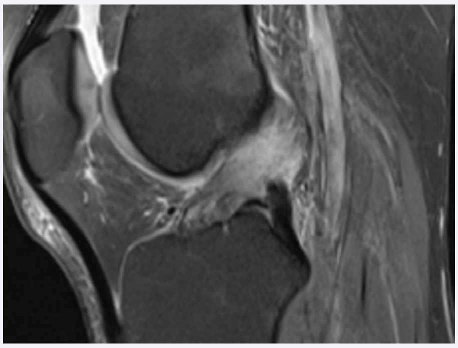

Figure 5 Partial tear of the ACL. Sagittal fat-suppressed proton density-weighted image shows partial discontinuity of the ligament fibers with hyperintensity.

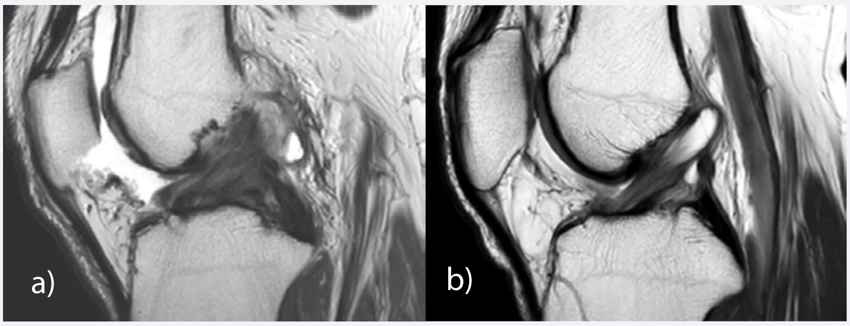

Figure 6 Imaging pitfalls in diagnosing ACL tears. (A) The ACL is thickened and ill-defined with increased signal intensity interspersed among visible intact fibers on sagittal T2-weighted image("celery stalk" sign), resulting from mucoid degeneration of the ACL. (B) A fusiform, lobulated lesion with fluid-equivalent signal intensity is noted interspersed within the ACL fibers. A ganglion cyst may be mistaken for a torn ACL.

the course of the ACL, either interspersed within the ligament fibers or surrounding the ligament (Figure 6B). It is important to make sure that the ACL bundles are intact from origin to insertion, when making the diagnosis of mucoid degeneration or ACL ganglia, to exclude partial tears.

ASSOCIATED INJURIES

The majority of ACL injuries are associated with medial or lateral meniscus injuries, and collateral ligament injuries. Detecting associated injuries of other stabilizing and supporting structures in the knee is important in surgical planning [81], and therefore should be sought for preoperative knee imaging.

Meniscal tears are frequently associated with ACL tears; the reported frequency is 39.6-73.0% [82-87]. Lateral meniscal tears are more commonly seen in acute ACL tear, whereas medial meniscal tears are more frequent in chronic injuries [88]. Meniscal tears are commonly located at the posterior horn, comprising 95% of the medial meniscal tears and 77% of the lateral meniscal tears [89]. Vertical longitudinal tear is the most common type of meniscus tear for both medial and lateral menisci in patients with ACL injuries [90-92] (Figure 7). Previous studies have reported that performing meniscus repair along with ACL reconstruction, may help restore knee kinematics, and improve patient-reported outcome [93-95].

The clinical significance of meniscal ramp lesions in patients with ACL tear has gathered attention in the past decade. Meniscal ramp lesions refer to the tear, disruption, or separation of meniscocapsular junction of the posterior horn of the medial meniscus, which usually occur after traumatic knee injuries. Undiagnosed ramp lesions may lead to knee instability (anterior translation and external rotational laxity), aggravation of medial meniscus posterior horn tear and accelerated degeneration of both the meniscus and the articular cartilage [96]. Therefore, it is important to recognize ramp lesions in patients sustaining ACL injury. On MRI, ramp lesions are noted as a thin fluid signal interposed between the posterior horn of the medial meniscus and the posteromedial capsule (Figure 2d).

Multiple ligament injuries involving at least one ligament other than the ACL is not uncommon. Medial collateral ligament injuries are reported to occur in 20-38% of patients sustaining ACL injury [97,98] (Figure 8). Among the two components of the MCL, the superficial component is a primary stabilizer against valgus stress, whereas the deep component is a secondary stabilizer resisting anterior tibial translation and provides minor stabilization against valgus stress [99]. In an ACL deficient knee, the MCL may be subjected to greater stress. Combined ACL-LCL injury also occur, and have been reported to be the second most common multi-ligament injury pattern [100]. Previous studies have consistently demonstrated that surgical treatment is superior to non-surgical treatment in multiple-ligament injured knee [101-103]. Therefore, it is important to recognize the injury of other ligaments in patients sustaining ACL injury.

Anterolateral ligament (ALL) injuries are found with varying severity and intensity in patients with acute ACL tear. ALL abnormalities have been reported to occur in 46 to 78.8% of ACL injuries in studies based on MR imaging [104,105] (Figure 9). The ALL functions as a stabilizer that resists anterior tibial translation, internal tibial rotation and pivot shifting, secondary to the ACL [106]. Failure to identify ALL injury may result in persistent instability following ACL reconstruction [107]. Concurrent reconstruction of the ACL and ALL significantly reduces internal rotation and axial plane tibial translation compared with isolated ACLR in the presence of ALL deficiency [108].

Posterolateral corner injuries are commonly associated with cruciate ligament injuries. A study based on MRI reported that among patients with ACL injury, 19.7% were found to have a concomitant posterolateral corner (PLC) injury [109]. Missed PLC injuries may lead to considerable morbidity, and therefore, should be sought for both clinically and radiologically. The three major stabilizers of the posterolateral corner, which are the fibular collateral ligament, the popliteus tendon and the popliteofibular ligament, should be evaluated on MRI in patients with ACL injury [110] (Figure 10).

TREATMENT OF ACL TEAR

Operative and non-operative treatment of ACL tears are

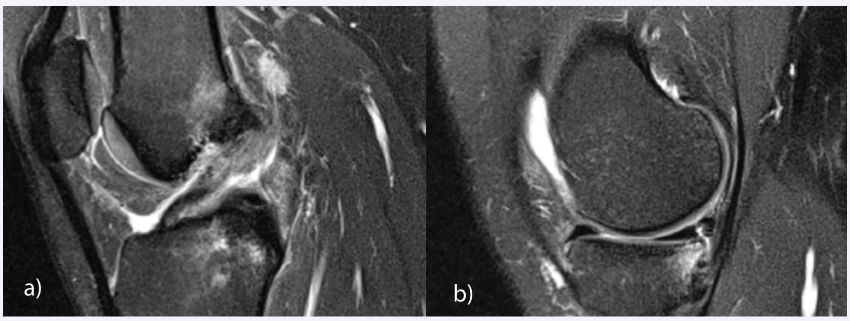

Figure 7 Associated injury of the meniscus. (A) Sagittal fat-suppressed – weighted image shows discontinuity of the ligament fibers with sagging of the ligament, and increased signal intensity. (B) A vertical longitudinal tear is noted in the posterior horn of the medial meniscus.

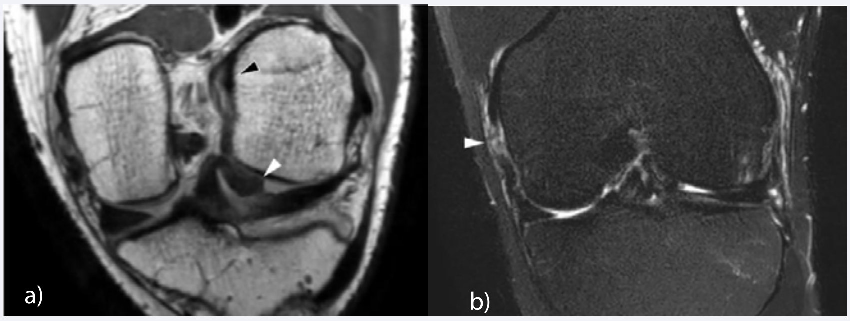

Figure 8 Associated injury of the medial collateral ligament. (A) Oblique coronal image shows complete detachment of the ACL from the femoral origin (black arrowhead) with the stump transposed beneath the lateral femoral condyle (white arrowhead). (B) Coronal fat-suppressed T2-weighted image shows a complete tear of the MCL (arrowhead).

Figure 9 Associated injury of the anterolateral ligament (ALL) and medial meniscus (A) Oblique sagittal T2-weighted image shows a complete tear of the ACL at the mid-substance. The proximal stump appears vertical to the Blumensaat line, whereas the distal stump appears horizontal. (B) On coronal fat-suppressed proton density-weighted image, the ALL shows increased signal intensity near the tibial attachment (arrow) and periligamentous edema, indicating injury of the ligament. Bone contusion is also noted at the lateral femoral condyle (arrowhead). (C) Axial fat-suppressed proton density-weighted image shows increased signal intensity of the anterolateral ligament (arrow) and bone contusion at the posterior aspect of the lateral tibial plateau (arrowhead). (D) A vertical longitudinal tear is noted at the posterior horn of the medial meniscus.

both considered acceptable options, depending on patient characteristics, including the activity level, sporting demands and the presence of concomitant injuries [81]. Some patients can functionally compensate for the instability after ACL injury and may be treated non-operatively with structured, progressive rehabilitation [111].

The goal of operative treatment is to restore the biomechanical stability of the knee and reduce secondary injury to the articular cartilage and menisci. For operative treatment of ACL injuries, ligament reconstruction with a tendon graft is considered the current gold standard [112]. Autografts, allografts, and synthetic grafts are available for reconstruction. Autographs include bone patellar tendon bone, hamstring, and bone quadriceps tendon grafts [113]. Both anatomical and non-anatomical ACL reconstruction techniques have been previously described. However, anatomical surgical techniques are considered superior, with better postoperative clinical scores, stability, and long-term outcomes of osteoarthritis development [81,114,115]. Selective bundle reconstruction technique refers to the isolated reconstruction of the injured AM or PL bundle with preservation of the non-injured bundle in partial ACL tear. Selective bundle reconstruction is advantageous in proprioceptive function due to the mechanoreceptors in the preserved ligament tissue [116].

Figure 10 Associated injury of the posterolateral corner. (A) A complete discontinuity is noted in the ACL on Sagittal T. (B) The popliteofibular ligament shows increased signal intensity on coronal fat-suppressed T2-weighted image (arrow). (C) Axial fat-suppressed T2-weighted image also shows increased signal intensity of the popliteofibular ligament along with periligamentous edema (arrow). Bone contusion is noted at the posterior aspect of the lateral tibial plateau (arrowhead).

Table 1: Primary and Secondary signs of ACL injury

	MRI finding
Primary signs	Discontinuity of the ligament fibers Failure of the ACL fascicles to parallel the Blumensaat line on sagittal image Nonvisualization of the ACL fibers
Secondary signs	Anterior translation of the tibia Uncovering of the posterior horn of the lateral meniscus Buckling of the PCL Kissing bone contusions involving the posterior aspect of the lateral tibial plateau and the mid portion of the lateral femoral condyle Deep sulcus sign Segond fracture

Abbreviations: ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

Recently, arthroscopic primary repair of ACL has been reported as a potential treatment option in proximal tears with sufficient tissue quality [117-120]. Experimental studies have shown that by preserving the native ligament, primary ACL repair may effectively restore the normal kinematics of the knee joint and protect the joint from degenerative changes [121]. MRI can play an important role in evaluating the location of injury and the quality of remnant ACL, to select those appropriate for primary repair. On MRI, ligament tissue is considered to be of good quality if the fibers are uniform and parallel and the signal intensity is homogeneous [119,122].

CONCLUSION

The ACL is an important stabilizing structure of the knee, providing resistance against anterior translational and internal rotational forces. MR imaging is an accurate and important tool in diagnosing ACL injuries, and various primary and secondary signs of ACL injury have been reported. It is important to recognize the characteristic imaging findings on MRI and correlate these findings with the injury mechanism. ACL injuries may be associated with injuries to other supporting structures of the knee, such as menisci, collateral ligaments, the anterolateral ligament, and structures of the posterolateral corner. The presence of associated injuries may alter the treatment plan, and therefore is important to diagnose on imaging.

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