Anterior Cruciate Ligament Injury: MR Imaging Diagnosis and Patterns of Injury

Erick M. Remer, MD
Steven W. Fitzgerald, MD
Harold Friedman, MD
Lee F. Rogers, MD
Ronald W. Hendrix, MD
Michael F. Schafer, MD

The anterior cruciate ligament (ACL) is an important stabilizer of knee motion. Injury of the ACL can lead to substantial disability; an accurate diagnosis of ACL injury is vital in both short-term and long-term patient care. Magnetic resonance (MR) imaging has emerged as the study of choice to evaluate the status of the ACL and other associated structures in the knee. Sagittal MR images have been commonly used in the evaluation of the ACL. However, the authors believe that coronal and axial imaging planes can add useful information about ACL injury and, thus, lead to improved accuracy and confidence regarding diagnosis. Multiplanar imaging can readily demonstrate meniscal, ligamentous, and bone marrow injuries that commonly occur with the most frequent mechanisms of ACL injury. These mechanisms, in order of frequency, include internal rotation and valgus stress, hyperextension, and varus stress with external rotation. An understanding of these mechanisms is helpful in the MR diagnosis of ACL injury.

INTRODUCTION
The anterior cruciate ligament (ACL) stabilizes the knee by preventing anterior translation and internal rotation of the tibia with respect to the femur. Loss of these restraints leads to substantial morbidity and can result in secondary dysfunction of other structures in the knee. Thus, early and accurate diagnosis of ACL injuries is...
important. However, despite being the most common ligamentous injury of the knee (1), most ACL tears are missed in initial clinical encounters (2).

The ACL is injured in field sports, skiing, motor vehicle accidents, and falls (2,3). Injuries most commonly occur from actions involving deceleration, twisting, or jumping. Because of the morbidity associated with the ACL-deficient knee, accurate diagnosis of ACL injury is essential for appropriate patient care. Making an accurate diagnosis, however, is often difficult because symptoms can mimic meniscal and other ligamentous injury. The clinical examination depends on the ability to demonstrate anterior tibial motion relative to a fixed femur (such as with the Lachman and pivot shift tests) (3). In the acutely swollen knee, these tests are difficult to perform because of pain and guarding; accuracy is thus diminished. Hemarthrosis seen at arthrocentesis is suggestive of a cruciate injury but is nonspecific (3).

Conventional radiographs have limited value in the diagnosis of acute ACL injury. Findings are indirect and limited to bone or soft-tissue abnormalities (4). Anterior tibial spine avulsion is a rare but specific finding (5). An exaggeration of the normal indentation in the middle third of the lateral femoral condyle (lateral "notch" sign) has been reported to be suggestive of an ACL tear (5). Arthrography has been used but is invasive and requires careful technique and interpretation (5). Its accuracy has varied in reported series (60%-97%) (6).

Magnetic resonance (MR) imaging has markedly expanded the role of radiology in the evaluation of acute knee injuries. Along with meniscal tears, injuries of the ACL were described in early reports of MR imaging of the knee (7-9). Although early studies demonstrated ACL tears, the reliability of ACL injury detection was not well established (10). Difficulties in diagnosing ACL injuries soon became apparent with use of straight sagittal images. Subsequent reports have emphasized the utility of angled sagittal images (11), double-oblique sagittal images (12), and T2-weighted sagittal images (13) to improve the accuracy of MR imaging in the diagnosis of ACL tears.

This article reviews the normal appearance of the ACL and signs of ACL injury as seen on sagittal, coronal, and axial MR images. We demonstrate the utility of coronal and axial images in the diagnosis of ACL injury and illustrate how reliance on the sagittal plane alone may lead to pitfalls in interpretation. Common mechanisms of ACL injury and their associated meniscal, ligamentous, and bone marrow abnormalities are discussed.

■ NORMAL ANATOMY

Knowledge of anatomic features of the ACL on MR images is essential to the detection of injury. The ACL is composed of collagen fibrils grouped to form 1-20-μm fibers. These ligamentous fibers merge to form larger subfascicular units that fan out into functional bands (14). Discrete anteromedial and posterolateral bands have been identified. The anteromedial band becomes taut in flexion, when most of the ligament is relaxed. In extension, the larger, posterolateral portion is under tension (15). These collagen-based bands are attached to bone by a transitional zone of fibrocartilage and mineralized cartilage. This transitional zone affords a gradual change in stiffness, thus helping prevent stress concentration at the two attachment sites of the ACL (16).

The ACL originates from the posterior medial surface of the lateral femoral condyle, where it attaches in a semicircle. Its larger and stronger tibial insertion is broad and fanlike and is in the anterior intercondylar area, slightly lateral and anterior to the anterior tibial spine (15). In this location, it is intimately associated with the anterior horn of the medial meniscus. The ACL is, on average, 4 cm long and 1 cm thick (17). Because of the orientation of its attachments to bone, the ACL turns on itself in an outward spiral as it courses anteriorly, medially, and inferiorly across the joint as it passes from the femur to the tibia. Along with the posterior cruciate ligament, the ACL is completely covered by synovium and is thus extrasynovial but intra-articular. The middle genicular artery, arising from the popliteal artery, is the primary supply to the ACL, with additional supply from the medial and lateral genicular arteries (17). Nerve fibers are supplied by branches of the tibial nerve (17).

■ PROTOCOL FOR MR IMAGING AND APPEARANCE OF THE NORMAL ACL

Imaging in 205 patients with arthroscopic correlation was performed with a dedicated knee coil on one of three units: Philips S5 (0.5 T) and S15 (1.5 T) (Philips Medical Systems North America, Shelton, Conn) or Hitachi 0.2 T (Hitachi Medical Corporation of America, Tarrytown, NY). Our standard protocol con-
Figure 1. Normal ACL. (1) Sagittal MR image (repetition time was 650 msec; echo time was 20 msec [650/20]) shows the normal ACL as a continuous low-signal-intensity band (arrow) extending from the femoral condyle to the tibia. (2a) Sagittal MR image (550/18) shows the straight margin of the ACL. Individual band or fiber bundles can be identified. Increased signal intensity is seen in the distal aspect of the ACL (arrow). (2b) Sagittal T2-weighted MR image (2,200/80) of the same patient shows an intact ACL with adjacent fluid. The ACL was unremarkable at arthroscopy. T2-weighted images are invaluable in the assessment of the ACL to help eliminate volume averaging of adjacent fluid. A zone of increased signal intensity in the distal portion of the ACL is a commonly observed finding in the normal ACL (arrow).

sisted of T1-weighted sagittal MR images (section thickness, 3.5 mm; field of view, 15–18 cm), coronal double-echo T2-weighted MR images (section thickness, 3.5–4.0 mm; field of view, 15–18 cm), and axial double-echo T2-weighted MR images (section thickness, 4.0–4.5 mm; field of view, 15–18 cm). Sagittal T2-weighted images and gradient-echo images in various planes were used to supplement this routine protocol. The multiplanar anatomy of the ACL has been demonstrated previously but, to our knowledge, has not been emphasized by other authors (18,19).

The primary plane used to diagnose ACL injury is the sagittal. Because most examinations are performed with the patient's knee extended, the ligament should be taut. Oblique sagittal images demonstrate the ACL more effectively than do straight sagittal images (11,12). These images are obtained by externally rotating the knee 10°–15° or internally rotating the imaging plane with the knee in normal anatomic position. On oblique sagittal spin-echo images, the ACL is a smooth, well-defined, low-signal-intensity structure coursing through the intercondylar notch (Fig 1,20). It may be seen as a solid continuous low signal band or three to four separate fiber bundles (13).

The normal ACL forms an approximately 45° angle to the long axis of the tibia and has a straight inferior margin. The inferior portion of the ligament has increased intrasubstance signal intensity, presumably due to the presence of fat and connective tissue above the tibial insertion (Fig 2). Depending on the section thickness used, the ACL is routinely demonstrated on only one or two consecutive sagittal images.
Figure 3. Normal ACL anatomy with a constant appearance on coronal MR images (2,200/30), with a section thickness of 4 mm. (a) Image shows the proximal ACL at the femoral origin as a thin, low-signal-intensity band paralleling the inner aspect of the lateral femoral condyle (arrow). (b) Image obtained through the central ACL adjacent to the horizontal portion of the posterior cruciate ligament again shows the ACL as a low-signal-intensity band as it begins to curve toward the tibial spine (arrow). (c) A more anterior image of the distal ACL demonstrates the normally expected increased signal intensity of its fanlike insertion (arrow). This signal intensity is thought to result from nonfibrous tissue as the distal ACL unwinds to insert itself on the anterior tibial spine.

Most ACL tears involve the middle substance of the ligament (90%) and, infrequently, the femoral (7%) or tibial (3%) attachments (1). The angle at which the image is obtained determines whether the femoral or tibial attachments are well seen. The distal end of the ACL is generally better seen than the proximal end because of partial volume averaging of the proximal ligament with the medial aspect of the lateral femoral condyle. If the distal and middle ACL is seen coursing in the proper direction and unassociated with a soft-tissue mass, it is usually normal even if the proximal end is not optimally seen (13).

On a series of coronal spin-echo images, the ACL can be traced from its posterosuperior and lateral origin to its anteroinferior and medial insertion. Again, the proximal two-thirds of the ACL has homogeneous low signal intensity and is well visualized with a section thickness of 4 mm.
intensity, whereas the distal ligament manifests increased signal intensity. Posteriorly, the ACL is readily identified adjacent to the horizontal segment of the posterior cruciate ligament as a linear or mildly convex low-signal-intensity band (Fig 3). As images proceed anteriorly, the ACL traverses the intercondylar notch obliquely to its tibial attachment. Depending on section thickness, the ACL is routinely shown on three or four consecutive coronal images.

**Figure 4.** Normal ACL anatomy on sequential axial MR images (2,200/30), with a section thickness of 4.2 mm. (a) Most cephalic image demonstrates the proximal ACL as an oval, low-signal-intensity structure (arrow). (b) Middle portion of the ACL has a more elliptic configuration as it begins to course obliquely within the femoral notch (arrow). (c) Distal ACL demonstrates increased signal intensity, also noted on previous sagittal and coronal images (arrow).

Axial images can also demonstrate normal ACL anatomy (Fig 4). Images that are more cephalic demonstrate the proximal ACL as a low-signal-intensity, ovoid or elliptic structure closely approximating the medial surface of the lateral femoral condyle. Axial images obtained in the middle portion of the ligament reveal a more pronounced elliptic configuration. Demonstration of the ACL on images obtained through the distal third of the ligament is difficult due to the severe oblique angle of insertion and the normally increased signal intensity in this area. Routine visualization of the ACL occurs on four to five axial images.
Figures 5, 6. ACL tears. (5) Sagittal MR image (650/20) demonstrates diffusely increased signal intensity within a poorly defined ACL (*). A complete tear of the middle substance of the ACL was identified at arthroscopy. (6) Value of T2-weighted images in the diagnosis of an ACL tear. (a) Sagittal T1-weighted MR image (650/20) reveals poor definition of the ACL with disordered fibers and increased signal intensity within the ACL substance (arrow). (b) Sagittal T2-weighted MR image (2,200/80) demonstrates the disruption of ACL fibers, diffusely abnormal signal intensity within the ACL, and a discrete band of high signal intensity within the proximal ACL (arrow). This complete proximal tear was confirmed at arthroscopy.

MR IMAGING OF ACL TEARS AND ASSOCIATED INJURIES

The earliest studies applying MR imaging to the evaluation of the knee demonstrated ACL injuries (7–9). Subsequent reports defined the accuracy of MR imaging in demonstrating ACL injury. In two series (13,20), the addition of T2-weighted sagittal MR images was documented to improve accuracy to 97%. Specific signs of ACL injury include irregular contour, discontinuity, focal or diffusely increased intrasubstance signal intensity, or poor visualization (Fig 5) (13,18,20). T2-weighted MR images allow high-signal-intensity joint fluid to be distinguished from a normal ligament (Fig 6). Areas of interstitial edema or hemorrhage are also manifested as increased signal intensity within the ACL tear on T2-weighted images. If volume averaging with the lateral femoral condyle is excluded, the finding of an intermediate-signal-intensity area on T1-weighted images that generally increases in intensity on T2-weighted images (with or without discontinuity) is indicative of a tear (1,18,20).
Figure 7. Injuries associated with ACL tears. (a) Sagittal MR image (2,200/30) obtained through the medial knee demonstrates abnormal posterior meniscal morphologic features and grade III intrameniscal signal intensity (arrow); these findings were consistent with tears and were confirmed at arthroscopy. (b) Coronal MR image (650/20) shows a diffusely swollen medial collateral ligament (short arrows) and an abnormal ACL (long arrow). Medial collateral and other ligamentous injuries are found in conjunction with ACL injuries, but these associated injuries have variable utility in the prediction of ACL injury.

### Associated Injuries Observed with MR Imaging (n = 205)

<table>
<thead>
<tr>
<th>Meniscal Injury</th>
<th>Normal ACL</th>
<th>ACL Tear</th>
<th>Bone Marrow Injury</th>
<th>Normal ACL</th>
<th>ACL Tear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial meniscal tear</td>
<td>48</td>
<td>43</td>
<td>Medial compartment</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Lateral meniscal tear</td>
<td>21</td>
<td>32</td>
<td>Lateral compartment</td>
<td>6</td>
<td>68</td>
</tr>
<tr>
<td>All meniscal tears</td>
<td>63</td>
<td>68</td>
<td>Lateral osteochondral</td>
<td>1</td>
<td>22</td>
</tr>
</tbody>
</table>

Note.—Numbers are percentages.

Although ACL injuries may occur in isolation, they are more commonly associated with other knee injuries. Commonly associated injuries are readily detected with MR imaging and include meniscal tears and injuries to other ligamentous structures. Meniscal tears (Fig 7a) have been reported at arthroscopy in approximately 65%-70% of patients with ACL tears (2). Our series demonstrated a similar number of meniscal injuries (68%) in patients with ACL injury (Table). Meniscal injuries, however, were also commonly observed (65%) in patients with normal ACLs at MR imaging and arthroscopy. The presence of meniscal injury was, therefore, not predictive of ACL injury. Associated injuries of the medial collateral ligament (Fig 7b), the lateral collateral complex, and the posterior cruciate ligament may be seen, depending on the severity and mechanism of injury. Medial collateral ligament injuries occurred more frequently in patients with ACL injuries (18%) than in those without ACL injury (4%) in our series.
Figure 8. Bone marrow injury associated with ACL injury. Sagittal MR image (650/20) through the lateral compartment reveals low signal intensity within the subarticular marrow of the middle portion of the lateral femoral condyle (solid arrows). The overlying cartilage appears intact. Geographic low signal intensity (open arrow) is also seen within the posterior aspect of the lateral tibial plateau. Bone marrow injuries, primarily involving the lateral compartment, are commonly observed in patients with ACL tears.

Figure 9. Osteochondral injury associated with ACL injury. Sagittal MR image (650/20) of an 11-year-old child with an acute ACL tear shows focal low signal intensity within the subchondral marrow (small arrows), an indentation of the cortex, and a focal area of abnormal signal intensity within the overlying articular cartilage (large arrow). Arthroscopy revealed a grade III chondral lesion and a lateral meniscal tear in association with ACL injury.

Recent reports have indicated that MR imaging can depict a broad spectrum of bone marrow injury (21–25). Occult bone injuries have been detected in the lateral compartment in 85%–97% of patients with ACL injuries (22,23). The injuries were primarily bone marrow contusions or osteochondral lesions. Bone marrow contusion and edema (Fig 8) involved the lateral compartment in 72% of patients with acute ACL tears in one series (22). In our series, the frequency was somewhat less (68%); however, our patients had acute, subacute, and some chronic ACL injuries. Despite the limitation that bone marrow injuries would be expected to resolve over time, lateral compartment bone marrow injury has a much higher predictive value with respect to ACL status than does meniscal injury (Table).

Osteochondral injuries of the lateral femoral condyle occur less frequently (20%) (21) but are more specific for concurrent ACL injury than lateral compartment contusion. This finding is the MR imaging equivalent of the plain radiographic notch sign discussed previously. It is seen in the lateral femoral condyle overlying the anterior horn of the lateral meniscus as a region of low signal intensity on T1-weighted MR images (Fig 9); the signal intensity increases on T2-weighted MR images and is accompanied by deformation or interruption of the articular cartilage.
Figures 10, 11. (10) Value of coronal images in ACL assessment. (a) Sagittal MR image (650/20) reveals poor definition of the ACL and focally abnormal signal intensity within the proximal ACL (arrow). (b) Coronal MR image (2,200/30) demonstrates a normal appearance of the ACL (straight arrow) and a posterior medial meniscal tear (curved arrow). Arthroscopy revealed a posterior meniscal tear and a normal ACL. This case illustrates the value of a multiplanar approach to the diagnosis of ACL injuries and the prevention of false-positive findings. (11) MR diagnosis of ACL injury on coronal images. Coronal MR image (2,200/30) obtained through the middle portion of the ACL reveals a diffusely swollen ACL with abnormally increased signal intensity (arrow).

■ MULTIPLANAR EVALUATION OF THE ACL

As we have indicated, we routinely use a multiplanar spin-echo knee protocol to evaluate a wide range of knee complaints and injuries. Despite the high accuracy rates of MR imaging in the diagnosis of ACL injury with sagittal images, pitfalls in image interpretation occur and can prove troublesome for either the experienced or infrequent reader. One problem is nonvisualization of the normal ACL on sagittal images. This problem has been reported to occur in 5%–10% of normal ACLs (18) and can be addressed by utilizing thin sections and routine oblique sagittal images oriented to the ACL axis (10°–20° of internal rotation). Partial volume effects can produce a false-positive appearance of ACL injury. On T1-weighted images, volume averaging of the lateral femoral condyle or adjacent joint fluid can produce a pseudomass that closely mimics ACL injury (1). This difficulty can be resolved with the use of thin sections, preferably with T2-weighting or multiple imaging planes.

Although other authors (1,26) have suggested that coronal images can contribute to accurate MR imaging examinations, these images have rarely been included in reports and presentations. We believe a multiplanar approach is essential to the accurate diagnosis of a wide range of knee injuries (Fig 10). The signs of ACL injury on coronal images are less commonly reported but do not differ substantially from those on sagittal images. We have found that focal or diffuse thickening, poor definition, and nonvisualization of the ACL were the most common signs found in evaluation of ACL injuries (Fig 11). Coronal images obtained through the intercondylar notch reveal ACL injury in the proximal, middle, and...
Figure 12. MR diagnosis of ACL injury on coronal images. (a) Coronal MR image (2,200/30) obtained through the intercondylar notch demonstrates nonvisualization of the ACL adjacent to the horizontal segment of the posterior cruciate ligament. Note the associated medial collateral injury (solid arrows) and lateral tibial edema (open arrows). (b) A more anterior image in the same patient helps confirm a lack of ACL fibers and shows a distal stump (arrow) attached to the anterior tibia spine. We refer to this appearance as the empty notch sign, which, in our series, had a 100% positive predictive value for ACL injury.

Figure 15. Internal rotation in valgus stress injury of the ACL. During internal rotation of the tibia (A), the ACL may be torn. If valgus stress is then also applied to the ACL-deficient knee, the posterior aspect of the lateral tibia can impact on the lateral femoral condyle, producing bone marrow or osteochondral injuries (shaded areas) within the lateral compartment. When the knee returns to a neutral position (B), the sites of bone marrow injury are no longer adjacent.

distal segments to equal advantage. In particular, the accuracy of diagnosis of proximal ACL injuries is improved with coronal images. An indistinct ACL on coronal images adjacent to the horizontal segment of the posterior cruciate ligament was most common in complete ACL tears, producing what we refer to as the "empty notch" sign (Fig 12). As previously noted in the section on normal anatomy, the distal third of the ACL manifests increased signal intensity on T1- and T2-weighted coronal images and should not be mistaken for injury.

Axial spin-echo sequences enable a cross-sectional assessment of ACL injury and, at times, a unique perspective on the status of the ACL. We have found an indistinct ACL, increased signal intensity within the ACL, and nonvisualization of the ACL to be predictive of ACL injury (Figs 13, 14). Although these findings are usually also observed on sagittal or coronal images, axial images serve to confirm initial interpretations and improve diagnostic confidence in questionable cases.
Figures 13, 14. MR diagnosis of ACL injury on axial images. (13a) Axial MR image (2,200/30) reveals a swollen ACL with abnormal high signal intensity consistent with a complete tear (arrow). Findings on sagittal and coronal MR images were also suggestive of an ACL tear. (13b) Axial MR image (2,200/30) in a patient with a confirmed ACL tear. The middle portion of the ACL is not visualized adjacent to the posterior cruciate ligament. This is the axial equivalent of the empty notch sign. Again, in this case, sagittal and coronal MR images demonstrated an ACL injury. (14a) Axial MR image (2,200/80) reveals abnormal ACL contour (arrow) and increased intrasubstance signal intensity. (14b) More cephalic axial MR image of the same patient shows a swollen ACL sheath with diffusely increased abnormal signal intensity (arrow). A complete ACL tear was found at surgery.

MECHANISMS OF ACL INJURY

Although ACL injuries can occur during a wide variety of activities, a few mechanisms account for the majority of ACL tears. An understanding of these mechanisms can contribute to accurate diagnoses both clinically and radiologically. The ACL serves as the primary restraint to anterior tibial translation and as a secondary stabilizer to resist internal tibial rotation (17). Therefore, the ACL would predictably be torn when the femur is externally rotated in relation to a fixed lower extremity or the tibia is internally rotated relative to the femur. This commonly occurs during falls while skiing, as well as in football and other field sports that may or may not involve contact.

A valgus stress component is frequently present. This mechanism can be appreciated schematically (Fig 15) and leads to a predictable constellation of associated findings. With
Figures 16, 17. (16) Internal rotation and valgus stress injury. (a) Sagittal reconstruction of three-dimensional gradient-echo data set (500/23, flip angle of 70°) demonstrates an ill-defined contusion within the middle portion of the lateral femoral condyle (arrows). (b) Adjacent sagittal MR image (500/23, flip angle of 70°) demonstrates contusion of the posterior tibial plateau (arrow). These contusions are not adjacent due to rotational forces at the time of injury. (17) Lateral compartment injury associated with internal rotation in valgus stress mechanism. Sagittal MR image (650/20) reveals an osteochondral defect (notch sign) in the middle portion of the lateral condyle (arrow).

rotation and valgus stress, the medial joint compartment is distracted, which can produce medial collateral injury. Medial meniscal tears, which are frequently peripheral, can also be present, and, along with ACL and medial collateral ligament tears, form the well-known O’Donoghue triad (25). Injury to the lateral compartment occurs in the form of impact injuries of the middle portion of the lateral femoral condyle with the posterior lateral tibia. In our experience, lateral meniscal tears are also common.

In our series, internal rotation and valgus stress was the most frequently observed mechanism of ACL injury. The presence of meniscal tears and medial collateral injury was variable, presumably related to the severity of stress applied and the precise vectors involved. Bone marrow injury of the lateral compartment was much more commonly noted (Fig 16), as has been previously reported (21–23). Injury of the articular surface of the lateral femoral condyle (Fig 17) (bone marrow signal intensity abnormality or osteochondral injury) was not associated with adjacent tibial contusion. Instead, tibial signal intensity abnormalities were posterior, consistent with the mechanism of internal rotation. Medial compartment bone marrow injuries were uncommonly observed.

The second most common mechanism of ACL injury, hyperextension of the knee, occurs much less frequently than does internal rotation. Hyperextension can occur during forward falls while skiing, jumping, and performing high kick maneuvers (26). Schematically, one can visualize how hyperextension results in an impact of the femoral condyles and the anterior tibia (Fig 18). ACL tears resulting from hyperextension frequently (70%) occur in isolation from meniscal or collateral ligament injuries (27). We have observed this
Figures 18, 19. Hyperextension injury of the ACL. (18) When hyperextension (A) of the knee occurs, the ACL can be torn in isolation from other meniscal or ligamentous injury. Anterior impact (shaded areas) of the femoral condyles and the tibia occurs. When the knee returns to a neutral position (B), these contusions are observed anteriorly and in direct approximation to each other. (19) Sagittal reconstruction of three-dimensional gradient-echo data set (500/25, flip angle of 70°) demonstrates contusions in adjacent regions of the anterior femur and tibial plateau (arrows) in addition to a disrupted ACL.

Figure 20. Varus stress injury. Coronal gradient-echo MR image (650/25, flip angle of 30°) demonstrates absence of the ACL and a lateral tibial rim avulsion fracture (arrow). The fracture is characteristically seen in patients with ACL injury caused by varus stress and external rotation.

pattern on MR images of patients with an appropriate history. ACL tears are seen in conjunction with anterior ‘kissing’ contusions of the condyles and the anterior tibia (Fig 19). Although we have surgical confirmation in only a few of the patients in this series, in our experience, this pattern of bone marrow injury has been highly predictive of isolated ACL injury.

A third and still less common mechanism of ACL injury is a result of varus stress with some component of external rotation of the tibia with respect to the femur. This produces some impact of the medial compartment while the lateral compartment is stressed. Typically, there is disruption of the middle component of the lateral collateral complex. This meniscotibial injury can result in ligamentous disruption or avulsion of the lateral tibial rim (Segond fracture) (22). This small fragment may be easily overlooked on conventional radiographs but is a clue to a high association of ACL injury, which leads to anterolateral instability of the knee and can be very disabling.

The MR appearance of Segond fractures was recently reported (27), and, in that series, ACL injury was present in 92% of cases. Although avulsion fragments were only visualized in 33% of cases at MR imaging (Fig 20), abnormal bone marrow signal intensity was observed at the lateral tibial rim in all cases. Our experience is similar, although, in our series, associated ACL tears were present in
all patients with Segond and Segond-like injury patterns. Variations included more severe disruption of the lateral complex, including the iliotibial band (Fig 21).

An understanding of mechanisms of ACL injury can lead to more accurate detection of injuries associated with ACL tears. In many cases, the information regarding associated meniscal or ligamentous injury is of greater value to the physician than is MR confirmation of ACL injury. Immediately after the injury, most ACL tears are treated conservatively with splinting and arthrocentesis if necessary (28). Acute ACL reconstructions are not routinely performed. In this setting, diagnostic information obtained with MR imaging can be vital in clinical decision making and patient counseling. The presence of associated meniscal tears, particularly unstable tears, or associated ligamentous injury may modify preoperative planning (29,30). The need for arthroscopic meniscal repair before ACL reconstruction can be determined with MR imaging.

■ SUMMARY

The short- and long-term sequelae of ACL injuries mandate diagnostic accuracy. MR imaging has been established as a highly useful method of accurately evaluating the ACL. However, we believe that a multiplanar approach can improve interpretive accuracy and diagnostic confidence. A multiplanar approach to ACL assessment can result from a dedicated multiplanar protocol or from the use of multiplanar reconstructions obtained with three-dimensional data sets. Although we supplement our knee imaging protocol with two-dimensional and three-dimensional gradient-echo sequences, we prefer a dedicated multiplanar approach based on T1- and T2-weighted spin-echo sequences to evaluate the ACL. This requires an understanding of normal ACL anatomy, variation, and injury in all planes. Some types of ACL injury, most notably, the “lax” ACL and some healed chronic tears (31), remain optimally demonstrated on sagittal images. T2-weighted MR images are essential for the accurate assessment of the ACL, independent of the imaging plane.

A multiplanar protocol is useful in documenting associated meniscal, ligamentous, and bone marrow injuries. Recognition of characteristic injury patterns on MR images and an understanding of common mechanisms of ACL injury are helpful in the accurate diagnosis of ACL and associated injuries. In particular, the detection of bone marrow injuries and an awareness of injury patterns, as demonstrated with a multiplanar approach, are helpful in predicting the mechanism of ACL injury.

■ REFERENCES