Imaging of the Postoperative Anterior Cruciate Ligament: Emphasis on New Surgical and Imaging Methods

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Abstract

The aim of anterior cruciate ligament (ACL) reconstruction is to restore normal function of the knee, but unfortunately abnormal kinematics and a predisposition to knee osteoarthritis occur in a significant percentage of patients. So there is an ongoing need to improve treatment options and long-term outcome of patients with a ruptured ACL. With the recent advancements in the field of ACL tissue engineering, the focus of treatment for ACL injuries is changing from resection and reconstruction toward repair and regeneration. Several new ACL repair methods were recently introduced as an alternative to traditional ACL reconstructive procedures. Radiologists must become familiar with these new surgical methods to interpret their appearance correctly on postoperative imaging studies. This article provides an overview of the latest advancements in ACL surgical methods and discusses the role of imaging to assess the postoperative ACL including both standard and advanced imaging methods.

Keywords

- anterior cruciate ligament (ACL) reconstruction
- ACL repair
- magnetic resonance imaging (MRI)
- quantitative MRI

One of the most challenging problems facing orthopedics today is the failure of tissues within the joint, such as the anterior cruciate ligament (ACL), to heal naturally after injury and surgical repair.[1,2] Therefore, surgical resection and reconstruction of the ACL is often recommended to facilitate a return to desired daily activities including sports. However, an incidence of osteoarthritis (OA) as high as 50% within 7 to 14 years after injury and reconstruction of the ACL is still a main drawback of this surgical strategy.[3] In contrast, a successful ACL repair can theoretically provide the patient with multiple advantages over surgical reconstruction, including preservation of the proprioceptive function of the ligament and the complex ligament insertion sites.[2]

Research in the field of ACL tissue engineering is ongoing and on the rise. Recently, several novel ACL repair techniques showed satisfactory outcomes in preclinical studies.[4,5] The potential success of these new ligament-preserving techniques may result in a realistic alternative for ACL reconstruction.

This article provides an overview of the latest advancements in ACL surgical methods and discusses the role of imaging for the assessment of the postoperative ACL, including recent developments in imaging and the new insights they may provide.

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ACL Injury and Repair

Native ACL Healing

In humans, the intra-articular ACL fails to heal after complete rupture.[2] This makes the ACL vastly different from other extra-articular ligaments in the body including the medial collateral ligament (MCL), which heals readily with functional bracing.[4] Initially, it was suggested that the lack of healing was due to the failure of the cells and blood vessels within and around the ACL to mount an adequate response.[4] Recent work found that the human ACL has a proliferative vascular and neurogenic response to rupture, a response similar to that found in the injured MCL.[2,4,5] In addition, there was no bridging of the gap between the ruptured ends of the ACL. Most connective tissues heal by filling the wound gap with a fibrin-platelet clot or provisional scaffold. The ACL wound site is not bridged by clot or connective tissue. Thus it was hypothesized that the failure of the ACL to heal was a result of a lack of wound-site filling.[2,4,5] The persistence of an unfilled gap in the wound site is also observed in meniscus, cartilage, and rotator cuff tendons, and all tissues within the intra-articular environment.

Several studies suggest that increased levels of so-called clot-busting enzymes that appear in the joint fluid shortly after trauma may prevent formation of a blood clot. This is a natural mechanism probably minimizing joint fibrosis after an injury, thus preserving motion within the joint and maintaining short-term function at the expense of tissue healing and long-term joint function.[2,4] The hypothesis is that filling the wound site in vivo with an appropriate substitute for a clot may lead to improved healing.[4,5] The ideal substitute scaffold has to be biocompatible and biodegradable to enable tissue ingrowth, and its mechanical properties should mimic the natural ACL as closely as possible. This is crucial for the native ligament to heal.[5]

ACL Graft Healing

Graft healing after ACL reconstruction occurs at two different sites: intra-articular graft remodeling, often referred to as ligamentization, and intratunnel graft incorporation.[6,7] Previous studies have demonstrated three characteristic stages of intra-articular graft healing after ACL reconstruction: an early healing phase with central graft necrosis and hypocellularity and no detectable graft revascularization of the graft tissue, followed by a phase of proliferation, the time of most intensive remodeling and revascularization, and finally, a ligamentization phase, with characteristic restructuring of the graft toward the properties of the native ACL.[2,6,7] However, full restoration of either the biological or biomechanical properties of the native ACL is never achieved.[6] In addition, successful ACL reconstruction requires solid bone tunnel healing. The mechanism by which graft-bone healing occurs depends on the type of the graft used.[6] For bone-patellar tendon-bone grafts, healing in the tunnel resembles normal fracture healing, with incorporation of the bone block in the tunnel observed as early as 16 weeks after surgery.[2,6,8]

The healing process occurs through a different mechanism after implantation of a soft tissue graft without bone plugs. First, fibrovascular interface tissue forms between graft and bone. Then progressive mineralization of the interface tissue occurs with subsequent bone ingrowth into the outer tendon and incorporation of the tendon graft into the surrounding bone. Progressive reestablishment of the continuity of the collagen fibers between the tendon and the bone results in a fibrous insertion of the tendon.[4,6] Complete bone tunnel healing of the ACL graft may occur as late as 6 to 12 months after surgery.[6,8] Several methods are used to improve bone tunnel healing, including both mechanical ways (e.g., lengthening the tunnel, minimizing the mismatch of graft-tunnel diameter, and providing circumferential contact between the graft and tunnel) and biological ways (e.g., use of osteoinductive cytokines such as bone morphogenetic proteins).[4,6,8] Unfortunately, a common cause for failed ACL reconstruction is still a failure of graft-to-bone healing.[6,8]

Surgical Treatment of ACL Injury

Historical Overview and Current Gold Standard

ACL surgery has evolved considerably over the past decades. The awareness of the inadequacy of direct suture repair (years 1895–1970) and nonanatomical ACL reconstruction techniques (extra-articular lateral tenodesis, late 1970s) led to an almost universal adoption of intra-articular ACL reconstruction (1980–today) for treatment of ACL injuries.[9,10] ACL reconstructions are most often performed with hamstring and bone-patella tendon-bone autograft tendons (►**Fig. 1**). The initial literature proposed bone tunnel placement for best graft isometry (full range of motion without causing ligament elongation and plastic deformation), but there is now compelling evidence to support anatomical tunnel placement (anatomical ACL reconstruction).[6,8] The transition from a

Fig. 1 Anterior cruciate ligament (ACL) reconstruction using hamstring autograft tendon. MRI was performed 14 months after surgery for recurrent knee pain. Sagittal proton-density-weighted image shows homogeneous low signal intensity of the healed ACL graft.

single-bundle to a double-bundle technique was recommended to reconstruct the anteromedial (AM) and posterolateral (PL) bundles separately to imitate the normal anatomy of the native ACL, thus helping to restore knee stability more effectively.[6,8] As of late, there have been reports of no difference in outcome measures between the two techniques, particularly when the reconstruction is anatomical.[6,8,11]

To improve outcomes, further modifications have been introduced to the ACL reconstruction technique such as selective (AM or PL) bundle augmentation in partial ACL tears, and, more recently, reconstruction with preservation of remnant ligament tissue.[6,8,11] Preservation of ACL remnants seems theoretically beneficial in terms of vascularity, proprioception, and kinematics. However, none of these modifications have been shown to make a significant difference to patient-reported outcomes. Moreover, retention of the ACL remnant tissue might lead to incorrect tunnel placement and cyclops formation.[6,8]

New Surgical Techniques

Several methods of primary ACL repair have recently been introduced including dynamic intraligamentary stabilization (DIS),[12] internal brace ligament augmentation (IBLA),[13] and primary ACL reconstruction using a degradable poly L-lactic acid (PLLA) scaffold.[14]

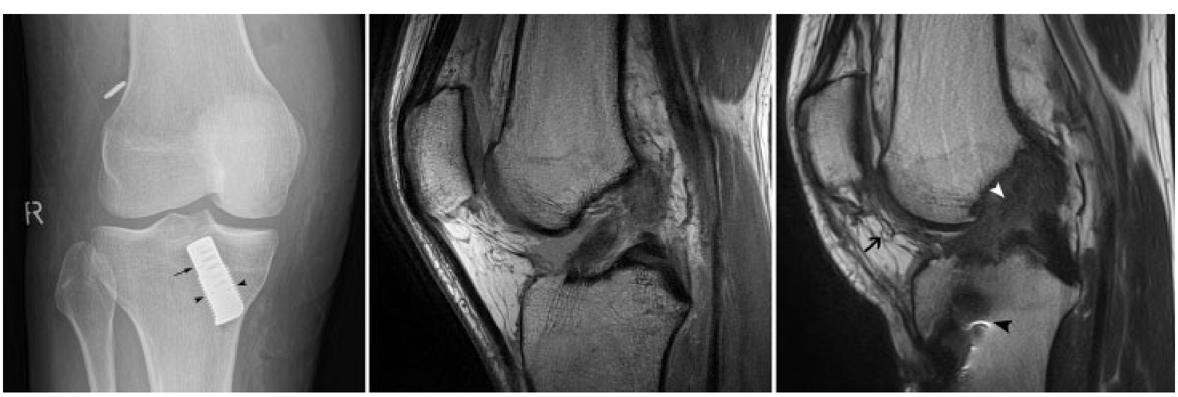
Generally, ACL repair needs to be performed relatively quickly after the initial injury because sufficient viable native ligament tissue must be present. Depending on the technique used, time to surgery after the rupture has to be < 3, 12, or 18 weeks. In contrast, ACL reconstruction is performed from the moment the knee function has recovered, mostly from 3 to 6 weeks, up to any time after the injury.[5,6,8]

DIS (Ligamys, Mathys AG, Bettlach, Switzerland) has been introduced for the repair of acute (time to surgery ≤ 3 weeks after injury) proximal or central ACL tears.[12] After microfracturing at the femoral footprint, the tibial remnants of the torn ACL are reduced to the femoral footprint by transosseous sutures. The knee is then stabilized with a strong polyethylene cord, which is anchored to the bone much like a standard ACL graft implant on the femoral side with a titanium flip anchor. The cord is pulled through the femur and the anatomical femoral footprint and passed behind the tibial footprint to prevent additional damage to the tibial ACL blood and nerve supply. It is brought under tension by a steel/Phynox screw-spring implant, which is placed at the anteromedial tibia (►**Fig. 2**). This mechanism acts as a dynamic internal fixator. It pushes the proximal tibia in a constant posterior drawer position (50 to 80N) in any degree of flexion, ensuring that the two ligament stumps are kept as close to each other as possible at all times to enable mechanically stable ACL healing.[15] The presence of the metallic implant in the tibia after DIS may complicate MRI follow-up in these patients and usually necessitates the use of metal artifact reduction sequences (e.g., slice encoding for metal artifact reduction[16]).

The efficacy of DIS in facilitating the self-healing of the ACL was analyzed in a sheep model, and complete healing of the torn ligaments was demonstrated through histologic examination.[17] Recently, clinical experience of the first 3 years after DIS in a large case series was reported.[18] The authors concluded that anatomical repositioning, along with DIS and microfracturing, leads to clinically stable healing of the torn ACL in most patients (96%). Most patients exhibited a normal knee function, reported excellent satisfaction, and were able to return to their previous levels of sporting activity.[18] However, longer term and comparative follow-up studies are required to determine whether the DIS technique improves clinical outcomes.

The IBLA (Arthrex, Naples, FL, USA) is a ligament repair bridging concept using braided ultrahigh-molecular-weight polyethylene/polyester suture tape and knotless bone anchors to reinforce ligament strength as a secondary stabilizer after repair and return to sports, which may help resist injury recurrence.[13] This technique involves repair of the ACL (time to surgery $\leq$ 12 weeks after injury) where it has ruptured close to its femoral attachment.

First, the torn ligament is reapproximated anatomically against the lateral femoral condyle, freshened with a microfracture probe. Second, the repair is protected by a 2-mm polyethylene tape through arthroscopically drilled femoral



a b,c

Fig. 2 Dynamic intraligamentary stabilization of the anterior cruciate ligament (ACL). (**a**) Anteroposterior radiograph demonstrating spring (arrow) screw (arrowhead) mechanism at the anteromedial tibia. Note titanium flip anchor at the lateral femoral cortex. (**b**) Preoperative sagittal proton-density-weighted image showing acute proximal tear of the ACL and large joint effusion. (**c**) Follow-up MRI at 6 months after surgery demonstrating clear continuity of the repaired ACL (white arrowhead). Note postoperative scar at Hoffa fat pad (arrow). Only minimal artifacts are seen at the tibia (black arrowhead) with use of slice encoding for metal artifact reduction.

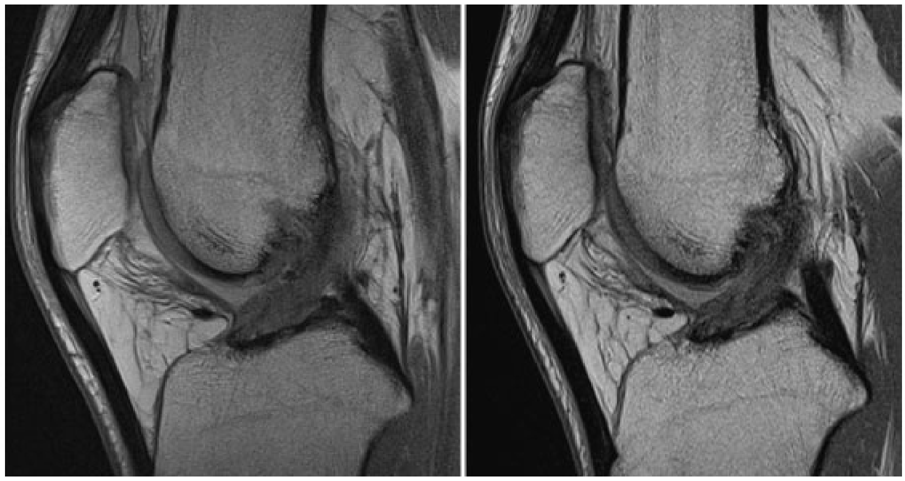


Fig. 3 Internal bracing of the anterior cruciate ligament (ACL). (**a**) Postoperative sagittal proton-density-weighted image at 5 months. (**b**) Follow-up MRI at 12 months showing decrease of the signal intensity of the ACL repair tissue, indicating tissue maturation.

and tibial bone tunnels (3.5 mm), bridging the anatomical attachments of the ACL in the mid-bundle position from tibia to femur. The tape is fixed on the femur with a titanium or steel flip anchor and on the tibia with a titanium bone anchor. The internal brace supports early mobilization of the repaired ligament and allows the natural tissues to strengthen progressively, protecting it against high strains that would impair the healing or even cause a rerupture during the healing process of the ligament[13] (►**Fig. 3**). The results of a recent study suggest that at minimum 1-year follow-up, IBLA is at least as effective in restoring stability and function of the knee as traditional ACL reconstruction surgery, with the greatest improvements seen in return to sporting activity.[19] Longer term follow-up and randomized studies are further required to compare IBLA directly against standard ACL reconstruction techniques.

Primary ACL reconstruction with resorbable PLLA scaffold (L-C Ligament; Soft Tissue Regeneration, Inc., New Haven, CT, USA) is intended for primary ACL reconstruction within 18 weeks of acute ACL rupture. It is a synthetic bioresorbable, three-dimensional (3D) braided polymer scaffold made from PLLA within and around which the native ACL will regenerate over time.[14] The L-C Ligament is composed of two tightly braided outer segments anchored in the bone tunnels (8 mm) much like standard ACL graft implants, and a more loosely braided central, intra-articular portion that extends into the apertures of the bone tunnels. The native (ruptured) ACL is left intact as much as reasonably possible with only minimal debridement of ACL stumps. In the short term, the scaffold is strong enough at the time of implantation to allow early functional rehabilitation of the knee. The PLLA scaffold is designed to capture migrating cells and slowly bioresorb over the postoperative period in parallel with neovascularization and native tissue ingrowth. This regenerative process eventually replaces the scaffold with native tissue (►**Fig. 4**). As resorption occurs, load-bearing responsibility transfers to the tissue ingrowth while mechanical integrity at the site is maintained by the resorbable polymer scaffold. Long-term in vivo performance and biomechanical properties of the L-C Ligament were evaluated in a sheep model, and healing of the torn ligaments with healthy regenerated ACL tissue and (near) complete resorption of PLLA was observed at 12 months, and no adverse effects noted through 4 years.[14] Further clinical studies are planned to compare ACL reconstruction with PLLA scaffold against autograft surgery with hamstrings.

Fig. 4 Primary anterior cruciate ligament (ACL) reconstruction with poly L-lactic acid scaffold. Postoperative paracoronal proton-density-weighted image at 12 months shows intermediate to high signal intensity of the ACL regenerated tissue in a clinically stable knee. (Image courtesy of Soft Tissue Regeneration, Inc., New Haven, CT; Dr. Kees van Egmond and Dr. Martijn Boomsma, Isala Clinics, Zwolle, the Netherlands.)

Imaging Techniques

Plain Radiography and Volumetric CT Scan

Although plain radiography is often the first imaging modality performed after ACL reconstruction (e.g., to assess hardware failure or dislodgment), a computed tomography (CT) scan is more reliable for evaluating the bone tunnels.[20] High-resolution volumetric CT acquisition with volume-rendering reconstructions has been used to describe critical bony landmarks of the ACL anatomical footprints that can aid in anatomical ACL reconstruction[21] (►**Fig. 5**). This method allows a view from a perspective similar to what is seen at the time of surgery. A grid orientation system can be used to assess femoral and tibial bone tunnel positioning. Commonly used terminology for femoral tunnel placement is shallow/deep and high/low because surgery is performed with the knee in flexion. The reported optimal placement for deep/shallow direction is a ratio of 27%, and 34% in the high/low direction, which corresponds to the anatomical femoral footprint.[22,23] The reported anatomical central tibial footprint position is located 39% from anterior and 48% from medial on the grid system.[24] Traditionally, the tibial tunnel has been placed more posteriorly in the footprint in an effort to avoid roof impingement. However, the most recent surgical trend is to aim for an anatomical central tibial tunnel location.[6,8,24] Bone tunnel orientation may vary according to the used drilling technique.[6,8,11] Transtibial tunnel drilling often results in nonanatomical placement of the femoral tunnel located high in the femoral notch (< 39 degrees to line parallel to the femoral shaft).[11] This increases the risk of vertical positioning in the intercondylar notch and positioning anterior to the native ACL attachment. The anteromedial portal drilling creates a femoral tunnel independent from the tibial tunnel, allowing for a more oblique positioning of the graft and for a tunnel that more closely resembles the native anatomical footprint.[8,11]

CT scan is the best modality for evaluating bone tunnel widening and the first choice modality in the management of

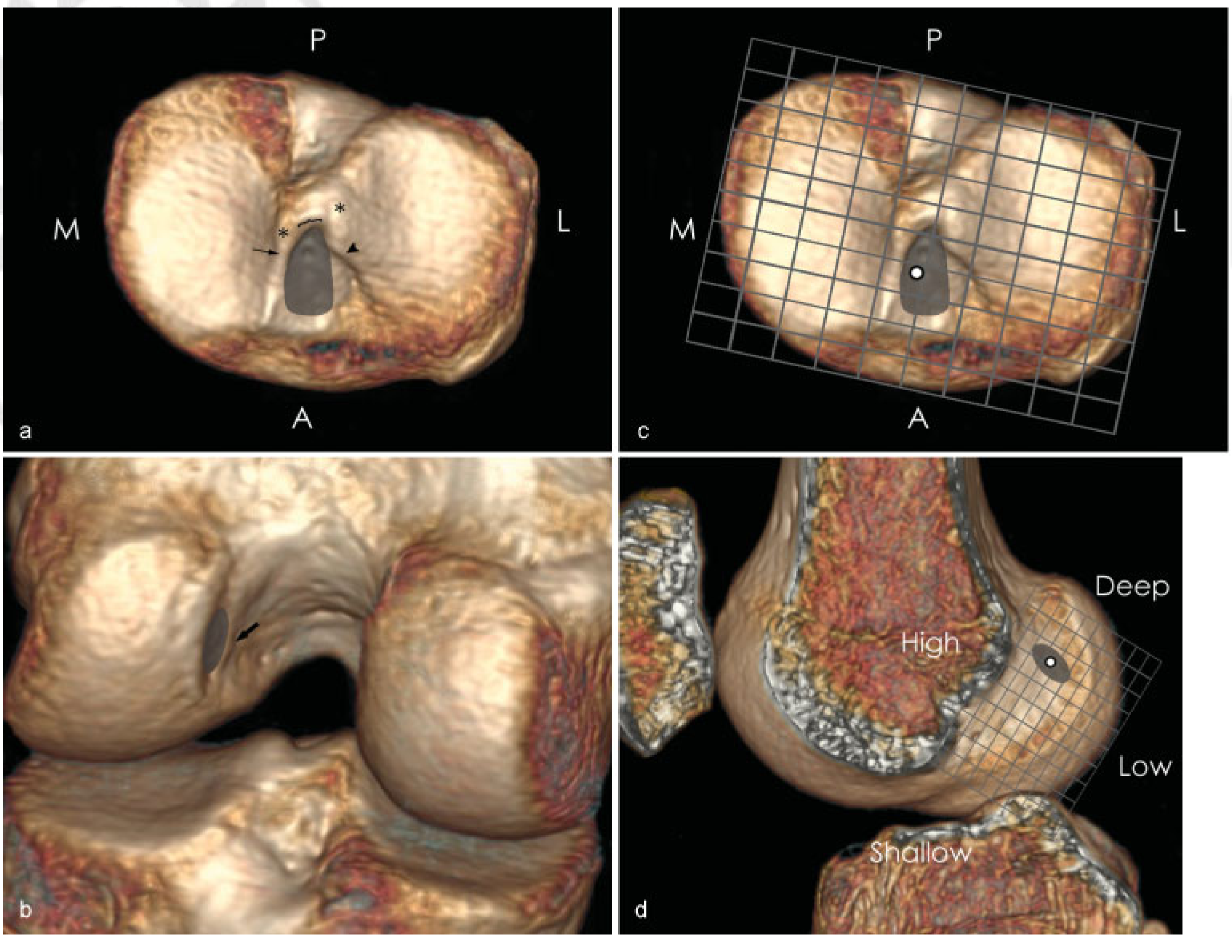


Fig. 5 Computed tomography (CT) scan with volume-rendering reconstructions showing anterior cruciate ligament (ACL) attachments (gray area). (**a**) Superior view of the left tibia. ACL fibers extend up to the base of the tibial spine, but none of them insert on the tibial spine. Posterior fibers of the ACL are seen just anterior to a bony ridge that runs between the medial and lateral tibial intercondylar tubercles (asterisks), called the tibial ACL ridge (curly bracket). Medially, ACL fibers insert directly onto the anterior extension of the medial intercondylar tubercle, the medial intercondylar ridge (arrow), near the lateral border of the articular surface of the medial tibial plateau. There is no distinct bony lateral or anterior border of the ACL tibial footprint (lateral intercondylar ridge, arrowhead). (**b**) Posterior view of the left knee showing femoral ACL attachment. Note bony ridge at the anterior margin of the femoral footprint, called resident's ridge (arrow). Grid orientation system at the (**c**) tibial and (**d**) femoral ACL attachment. The reported optimal placement of bone tunnels is marked by a white dot in the footprint (see text for details).

ACL revision surgery to assess bone stock quality and bone graft incorporation.[20,25] The radiolucency around the graft associated with tunnel widening is the apparent result of bone resorption in the insertion site area.[25,26] This finding is supported by MRI data, showing fluid signal, rather than bone signal, surrounding the tendon. The presence of bone resorption at the graft insertion site as early as 3 months after ACL reconstruction needs to be followed closely.

Conventional MR Imaging

MRI is commonly used as a clinical tool for qualitatively monitoring ACL graft status after surgical reconstruction.[27] The healed ACL graft has low signal on conventional MRI (►**Fig. 1**). Intermediate signal may be seen within grafts from ~ 4 to 8 months after surgery due to graft remodeling, decreasing with time and usually completely resolving by 12 months.[7,27] Similarly, bone tunnel healing may be observed on MRI with high signal intensity at the initial bone–tendon interface gradually changing to low signal intensity due to progressive maturation and ossification of the fibrous tissues.[26]

Although human biopsy studies have shown that neovascularization of a tendon autograft occurs, the extent of vascularity is below the threshold detectable with gadolinium-enhanced MRI using conventional sequences.[7,28] On the contrary, enhancement of the richly vascularized periligamentous soft tissues can be seen on conventional MRI.[28]

In the setting of a reinjury or a poorly functioning graft, the reconstructed ACL is difficult to assess on MRI. A study by Waltz et al[29] in 2014 found a 60% sensitivity and a 87% specificity of MRI to detect an ACL graft tear. Moreover, the status of the ACL graft on MRI may not correlate well with the actual function of the graft.[29–31]

Preoperative MRI must be performed relatively quickly after the initial injury in patients for whom ACL repair is considered. In particular, the DIS technique is suited for ACL ruptures not older than 2 or 3 weeks. Importantly, radiologists should describe ACL rupture location (proximal, central or distal third) and status of the ligament stumps (single strand, two bundles, three or more strands) because this technique is intended for proximal or central ACL ruptures.[18]

MRI also documents the healing process after primary ACL repair. The signal intensity of the repaired ACL depends on the integrity of the scaffold, the extent of tissue ingrowth, and its degree of maturation (►**Fig. 3**). The PLLA scaffold gives a uniform low signal on MRI when freshly placed. This low signal is slowly lost by the progressive regeneration and ingrowth of native ACL tissue. As the PLLA continues to be degraded over the postoperative period, the regenerated ACL may still display intermediate or high signal intensity on MRI, even in a clinically stable knee (►**Fig. 4**). Dynamic contrast-enhanced MRI may be useful to monitor ACL healing and help differentiate between ACL repair tissue and postoperative scar (►**Fig. 6**).

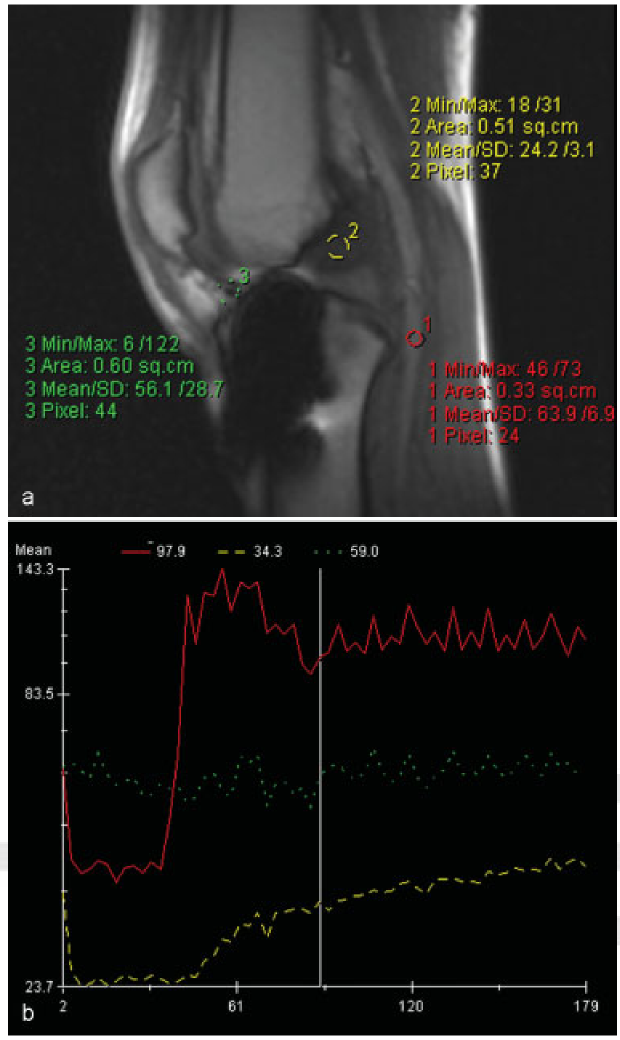


Fig. 6 Dynamic contrast-enhanced MRI after dynamic intraligamentary stabilization of the anterior cruciate ligament (ACL). (**a**) Region of interest measurements in ACL repair tissue (yellow), Hoffa scar (green), and popliteal artery (red). (**b**) Dynamic contrast curve shows marked hypervascularity of ACL repair tissue compared with lower vascularity in the postoperative scar.

Advanced MR Imaging

MR parameters of volume (a measure of tissue quantity) and signal intensity (a surrogate measure of tissue quality) have been found to correlate with the biomechanical properties of an ACL graft and can predict clinical, functional, and patient-oriented outcome measures after ACL reconstruction.[31,32] Because the use of signal intensity as an outcome measure is limited by its dependence on image acquisition parameters and scanner manufacturer, T2 and T2* relaxation time variables are used to standardize MR results[31,33] (►**Fig. 7**). These time variables are inherent tissue properties that reflect specific tissue characteristics and correlate well with the level of tissue organization.[31–33] Future work will be needed to validate longitudinally this MRI-based prediction method to document within-patient temporal changes relating to ACL strength and to determine the appropriate timing for athletes to return to sports.[32]

Diffusion tensor imaging (DTI) can be used to image and visualize the structure of the ACL and ACL graft, and it can provide additional information over conventional MRI.[34] It is a technique particularly suited for the evaluation of highly

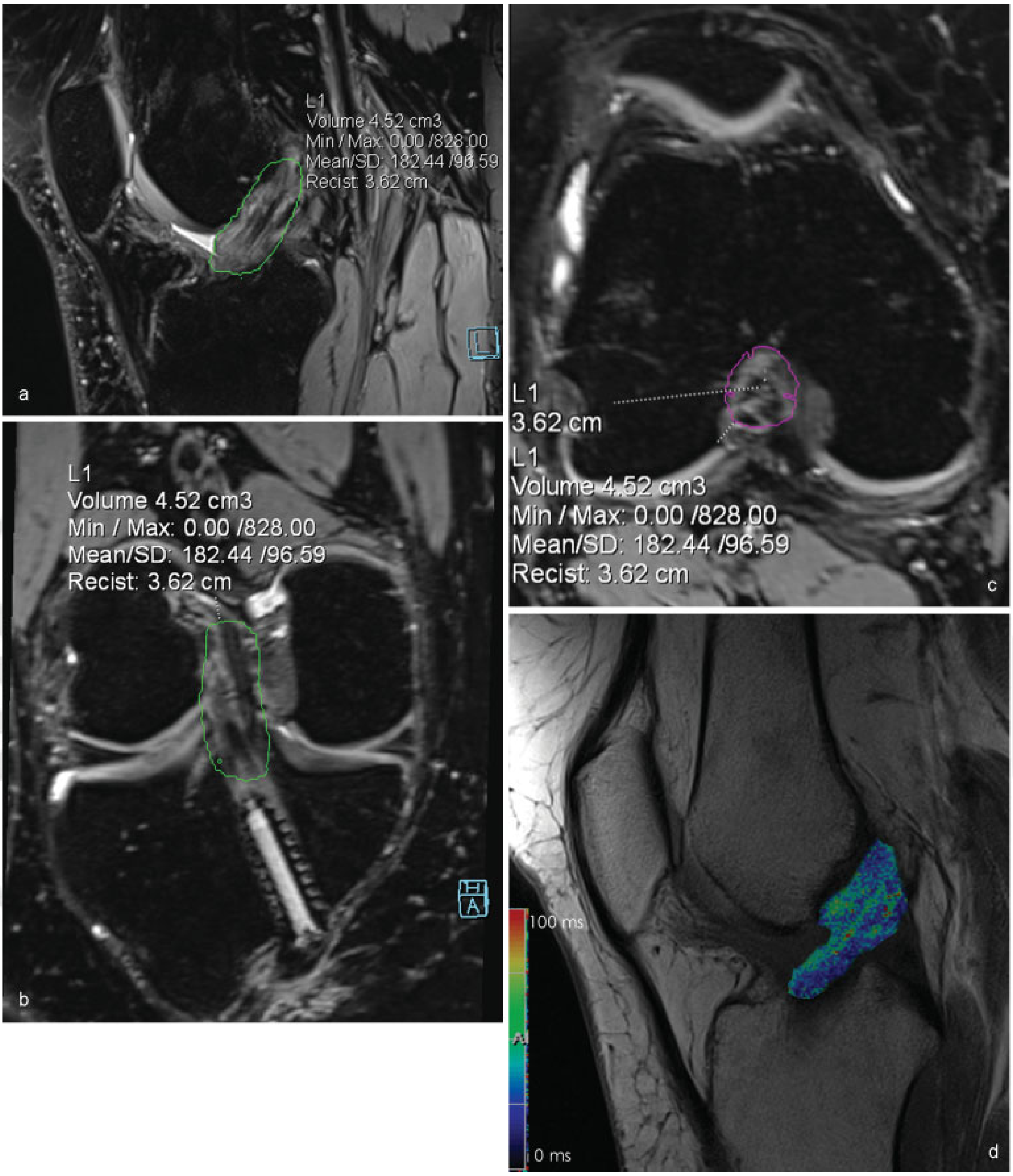


Fig. 7 MRI-based volume measurements and quantitative T2 mapping of anterior cruciate ligament (ACL) graft in clinically stable knee. (**a**) Sagittal, (**b**) coronal, and (**c**) axial three-dimensional fs turbo spin-echo images showing volume measurements of intra-articular ACL graft. (**d**) Quantitative T2 mapping.

organized tissues and provides quantitative parameters of the fiber bundles, such as fractional anisotropy and apparent diffusion coefficient values. Although ligament DTI is technically challenging because of the small volume of tissue, previous studies showed the feasibility of DTI of the ACL graft.[34,35] In the author's institution, DTI of the knee is performed on a clinical 3-T MR imaging system (Magnetom PRISMA^{fit}, Siemens AG, Erlangen, Germany) using a 15-channel knee coil and a spin-echo–based echo-planar imaging sequence (336 axial slices; voxel size 1.5 mm × 1.5 mm × 6 mm; field of view 192 mm × 192 mm; TR/TE 1300/45 msec; b-values 0 and 400 s/mm^2; and acquisition time, 7 minutes, 25 seconds) (►**Fig. 8**). Further studies are needed to investigate the ability of DTI to monitor quantitatively the healing ACL and to detect ACL graft pathology.

Ultrashort echo time imaging (UTE) is generally applied to techniques using shorter radiofrequency excitation pulses and faster readout methods than conventional methods to produce

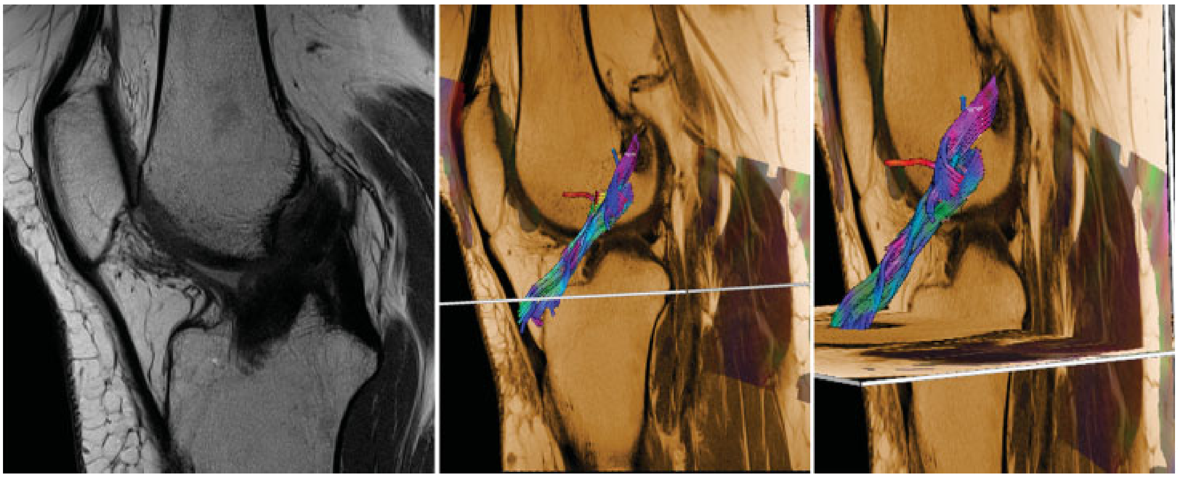


Fig. 8 Diffusion tensor imaging of anterior cruciate ligament (ACL) graft. (**a**) Sagittal proton-density weighted image demonstrates intact ACL graft. (**b**) Sagittal and (**c**) oblique three-dimensional views of fiber tractography showing gross morphology of the ACL graft.

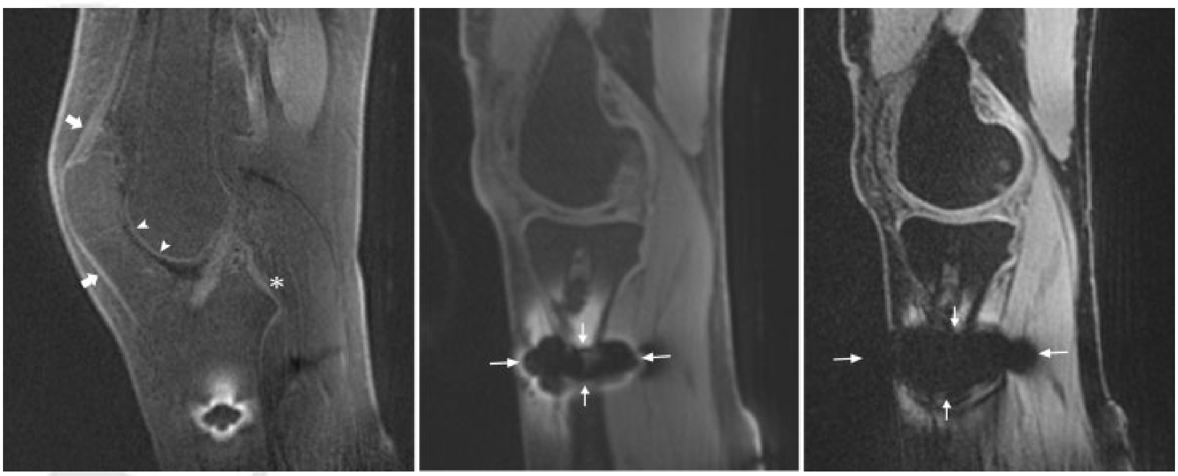


Fig. 9 Ultrashort TE (UTE) MR imaging after anterior cruciate ligament (ACL) reconstruction. (**a**) UTE subtraction image (same patient as Fig. 1) shows high signal intensity of the ACL graft. High-intensity linear signal near the osteochondral junction at the trochlea (arrowheads), extensor apparatus (arrows), and posterior cruciate ligament (asterisk) can also be seen. (**b**) Sagittal UTE images with 60 µs and (**c**) 3.92 ms TEs show more pronounced dephasing artifact surrounding hardware fixation at the longer TE.

images with very short TEs, typically in the range of 8 to 250 µs.[36,37] As a result, signal can be acquired from short T2 structures, such as tendons and ligaments. Several UTE techniques focusing on the method of image acquisition have been developed.[38,39] The author's institution uses a dual-echo 3D UTE sequence with minimum TE = 60 µs. Difference images are formed to suppress signals from long T2 components by subtracting the later echo time (TE = 3.92 msec) image from the first image (TE = 60 µs). As with conventional MR techniques, UTE can also be used for quantitative T2* mapping of tissues.[38]

UTE imaging provides new options to visualize anatomy and demonstrate disease of the knee. Also, contrast enhancement within the normal and injured ACL can be observed with use of UTE sequences. Finally, UTE imaging can be used to reduce susceptibility artifacts from metallic implants.[36,37] This may improve visualization of the bone tunnels after ACL surgery and ultimately may lead to better assessment of bone tunnel healing (►**Fig. 9**).

Conclusion

1. The surgical trend toward anatomical ACL reconstruction necessitates the use of imaging studies.
2. Novel ACL repair techniques are increasingly being performed as an alternative to ACL reconstruction to improve clinical outcomes. These repair techniques have to be performed within several weeks after the rupture. This requires the prompt availability of MRI.
3. Volumetric CT is the golden standard for the evaluation of bone tunnel placements after ACL surgery.
4. The repaired or regenerated ACL may display high signal intensity on MRI, even in a clinically stable knee.
5. Advanced MR techniques can be used as an adjunct to conventional imaging to monitor the healing ACL quantitatively. UTE imaging may provide new options to visualize the postoperative ACL.

Conflict of Interest
The first author (P.V.D.) is a consultant for and has received compensation from Soft Tissue Regeneration, Inc., New Haven, CT, USA.

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