Direct magnetic resonance (MR) arthrography with injection of saline solution or diluted gadolinium can be useful for evaluating certain pathologic conditions in the joints. It is most helpful for outlining labral-ligamentous abnormalities in the shoulder and distinguishing partial-thickness from full-thickness tears in the rotator cuff, demonstrating labral tears in the hip, showing partial- and full-thickness tears of the collateral ligament of the elbow and delineating bands in the elbow, identifying residual or recurrent tears in the knee following meniscectomy, increasing the certainty of perforations of the ligaments and triangular fibrocartilage in the wrist, correctly identifying ligament tears in the ankle and increasing the sensitivity for ankle impingement syndromes, assessing the stability of osteochondral lesions in the articular surface of joints, and delineating loose bodies in joints. Indirect MR arthrography with intravenous administration of diluted gadolinium may be performed when direct arthrography is inconvenient or not logistically feasible. Although indirect MR arthrography has some disadvantages vis-à-vis direct MR arthrography, it does not require fluoroscopic guidance or joint injection and it is superior to conventional MR imaging in delineating structures when there is minimal joint fluid. In addition, vascularized or inflamed tissue will enhance with this method. Indirect MR arthrography can be used to rule in or diagnose abnormalities and to exclude abnormalities.
Introduction

Magnetic resonance (MR) arthrography is increasingly being used to evaluate certain joint disorders. In this article, we address the global considerations regarding this technique as well as more joint-specific issues. We discuss the use of direct MR arthrography in joints and provide an overview of the indirect form of MR arthrography.

Direct MR Arthrography

In magnetic resonance (MR) imaging of joints, diagnostic success requires delineation of complex anatomic structures and demonstration of subtle abnormalities. MR arthrography extends the capabilities of conventional MR imaging because contrast solution distends the joint capsule, outlines intraarticular structures, and leaks into abnormalities. MR arthrography exploits the natural advantages gained from joint effusion and is possible in any joint in which conventional arthrography is performed.

Either saline solution or diluted gadolinium may be injected as the MR arthrographic contrast material, but the majority of authors have chosen to investigate the role of the latter (1–8). Saline solution has diagnostic disadvantages compared with diluted gadolinium and does not overcome several major shortcomings encountered in conventional MR imaging. For example, in the shoulder, injected saline solution is isointense relative to bursal effusion in the subacromial-subdeltoid space. Thus, despite the leak of saline solution across the cuff tendon, it still may not be possible to differentiate partial- from full-thickness tear.

Radiologists should consider several issues before offering MR arthrography. The procedure converts MR imaging from a noninvasive examination into a mildly invasive one, exposing patients to ionizing radiation as well as the risk of intraarticular needle placement. The study requires the coordination of scheduling in two procedure rooms and becomes impractical if the fluoroscopy suite is too distant from the MR imager. Although gadolinium-based contrast agents have not been approved by the U.S. Food and Drug Administration for intraarticular injection, most radiologists no longer feel obliged to obtain approval from an institutional review board. Finally, the test is more expensive than either arthrography or conventional MR imaging.

Technique

The T1-weighted signal intensity of contrast material depends on the concentration of gadolinium and the magnetic field strength. To optimize the paramagnetic effect of gadolinium at 1.5 T, pharmacuetic preparations should be diluted to a concentration of 2 mmol/L (9). There are numerous ways to obtain this concentration, depending on whether iodinated contrast material is mixed with the gadolinium. If iodinated contrast material is used, 0.8 mL of gadopentetate dimeglumine or some other form of gadolinium can be added to 100 mL of normal saline solution. Ten mL of this solution can then be mixed with 5 mL of iodinated contrast material and 5 mL of lidocaine 1% (final gadolinium dilution ratio = 1:250). Following aspiration of any joint fluid, this mixture is injected until the joint capsule is properly distended (approximately 12 mL in the shoulder). Single-contrast technique is necessary to avoid magnetic susceptibility artifact from intraarticular gas. The use of iodinated contrast material allows fluoroscopic confirmation of intraarticular needle placement and acquisition of standard pre- and postexercise arthrographic spot images.

MR imaging should be initiated within 30 minutes following arthrography to minimize absorption of contrast solution and loss of capsular distention. The same dedicated coils and imaging planes are used in both MR arthrography and
conventional MR imaging. T1-weighted spin-echo pulse sequences, with or without fat suppression, maximize the signal intensity of contrast solution. A T2-weighted sequence is helpful in the identification of extraarticular fluid collections, such as labral cysts, and the characterization of incidental bone marrow lesions or periartricular masses. With use of fat suppression, T2-weighted images can demonstrate subtle marrow edema.

**Pitfalls**

Diagnostic difficulties may arise because fat and gadolinium have similar signal intensities on T1-weighted images. In high-field systems, frequency-selective fat suppression makes use of the difference in the precessional frequencies of fat and water (chemical shift) by applying a presaturation pulse that is identical to the precessional frequency of fat. Mid- and low-field systems can achieve fat suppression with phase-shift techniques that create separate sets of images for water and fat. Because the signal from fat is decreased and the signal from contrast solution is preserved, fat-suppressed images delineate the boundary between contrast solution and fat and accurately demonstrate extraarticular contrast material.

Diagnostic difficulties can also result from extraarticular injection or leak of contrast material through the capsular puncture site. For example, in the shoulder, extraarticular contrast material can spread along fascial planes into the subacromial-subdeltoid space, creating a “bursogram” that can be mistaken for a full-thickness rotator cuff tear. Injecting less than 15 mL into the joint decreases the likelihood of extraarticular leak. To avoid contrast material injection into the subscapularis tendon or inferior glenohumeral ligament (IGHL), a posterior approach may be preferable if anterior glenohumeral instability is suspected.

Inadvertent injection of gas into the joint may lead to a false-positive diagnosis of intraarticular loose bodies. However, gas bubbles will rise to nondependent regions of the joint, whereas loose bodies will gravitate to dependent locations.

**Shoulder**

**Rotator Cuff.**—On MR arthrographic images, intraarticular contrast solution outlines the inferior cuff surface, fills partial cuff tears, and, in full-thickness tears, leaks from the glenohumeral joint into the subacromial-subdeltoid space (1–3). This leakage confirms the diagnosis of full-thickness cuff tear (Figs 1, 2). Thus, the presence or absence of extraarticular contrast solution allows differentiation of full-thickness from partial-thickness cuff tears. The sensitivity and specificity of MR arthrographic images in the diagnosis of full-thickness tear are comparable to those of conventional arthrography (ie, they approach 100%).

The usual impingement-related cuff tear is horizontal in configuration and begins at the anterior margin of the supraspinatus tendon. It propagates posteriorly into the infraspinatus tendon, which explains why larger tears always show the greatest degree of tendon retraction anteriorly. MR arthrographic images may facilitate the accurate measurement of horizontal cuff tears in terms of their anteroposterior dimension and their retraction from the greater tuberosity. Full-thickness vertical tears are relatively uncommon compared with horizontal tears and represent a longitudinal split in tendon fibers. Because there is no tendon retraction, they are difficult to diagnose on conventional MR images. On MR arthrographic images, vertical tears are visible because they fill with contrast material.

MR arthrographic images are particularly well suited to the diagnosis of partial-thickness tears,
which usually begin at the articular (inferior) surface of the supraspinatus tendon (Fig 3). In this location, high-signal-intensity contrast solution can fill these defects and demonstrate planes of tendon delamination. Partial-thickness tears often propagate within the tendon without extending to the bursal surface. Bursal (superior) and interstitial partial-thickness tears do not fill with contrast material and may be overlooked on T1-weighted arthrographic images. MR arthrographic protocol should include T2-weighted imaging, which is used to identify these bursal tears in a manner similar to conventional MR imaging, as well as bursal fluid collections (Fig 3).

Diagnostic accuracy is increased when fat-suppressed images are acquired (3). Partial- and full-thickness cuff tears may not be distinguishable on standard T1-weighted images because fat and gadolinium have similar signal intensities. The greatest diagnostic difficulty occurs whenever cuff tendons show contrast solution that extends to the bursal surface but not definitely through it (Fig 4). On fat-suppressed T1-weighted images, the signal intensity of contrast solution is unchanged, whereas the signal intensity of normal fat is selectively decreased. Thus, persistent high

Figure 3. Large partial-thickness surface rotator cuff tears. (a) Coronal oblique fat-suppressed T1-weighted MR arthrographic image (450/18) demonstrates a contrast material collection in an inferior surface defect (arrow). No contrast material is present in the subdeltoid space, a finding that indicates a partial-thickness tear. (b) Adjacent T2-weighted MR arthrographic image shows focal fluid at the superior tendon surface (arrows). This defect was overlooked on T1-weighted images. Large partial-thickness cuff tears were surgically repaired.

Figure 4. Inferior partial-thickness surface rotator cuff tear. (a) On a coronal oblique T1-weighted MR arthrographic image (450/18), contrast material (white arrow) appears to cross the entire cuff tendon. Low-signal-intensity fluid is present in the subacromial space (black arrow). (b) On a corresponding fat-suppressed MR arthrographic image, the contrast material (white arrow) remains contained within the supraspinatus tendon, a finding that confirms the diagnosis of a partial-thickness cuff tear. The bursal effusion remains low in signal intensity (black arrow). A subtotal cuff tear was surgically repaired.
signal intensity in the subacromial-subdeltoid space indicates a full-thickness cuff tear, whereas low signal intensity indicates a partial-thickness tear. Fat suppression also improves diagnostic accuracy in the detection of small partial-thickness tears at the inferior cuff surface.

Glenoid Labrum and Labral Ligamentous Complex.—On MR arthrographic images, the majority of anatomic variants are easily distinguished from labral abnormalities (Figs 5, 6). Articular cartilage that undercuts the labral fibrocartilage is rarely a source of diagnostic difficulty because the cartilage has lower signal intensity than the contrast solution. Whereas cartilage has uniform thickness, sublabral contrast material in a tear demonstrates variable width. Normal glenohumeral ligaments are distinguished from torn labra because the ligaments can be followed away from the glenoid rim until they merge with the distended capsule. In contrast, torn labral fragments can be followed back to the glenoid rim on sequential MR arthrographic images.

Some anatomic variants continue to create diagnostic problems on MR arthrographic images. Morphologic criteria may not be sufficient to distinguish a small, normal labrum from a blunted, deficient labrum. Normal sublabral sulci can mimic tears because they occur at the interface of the labrum with the articular cartilage and become filled with contrast solution (5,10). Occasionally, the labrum can be completely detached (sublabral hole or foramen). As normal sulci increase in size with age, the labrum becomes progressively separated from the glenoid rim, mimicking a displaced labral fragment. These variations in the appearances of sulci lead to both false-negative and false-positive diagnoses. The most common locations of sulci include the superior labrum at its junction with the bicipital tendon and the anterosuperior labrum between the origins of the middle and inferior glenohumeral ligaments (Fig 7).
One of the major advantages of MR arthrography is visualization of the labral-ligamentous complex, which consists of the glenoid labrum in combination with the superior, middle, and inferior glenohumeral ligaments. The glenohumeral ligaments reinforce the joint capsule and function as a unit with the glenoid labrum, which anchors the ligaments to the glenoid rim (5,6,11,12).

By demonstrating the inferior labral-ligamentous complex, MR arthrography makes a major contribution to the evaluation of patients with suspected glenohumeral instability. The anterior band of the IGL is critical in maintaining passive anterior stability of the shoulder and functions as a unit with the glenoid labrum, which anchors the ligament to the glenoid rim (11,12). The origin of the IGL creates a stress point on the labrum. Excessive tension can avulse the labrum from the glenoid rim, rendering the ligament incompetent.

Specific MR arthrographic criteria can be used in the differentiation between stable and unstable shoulders because these images can show the location and length of labral abnormalities relative to the origin of the IGL. If the torn labral segment involves the attachment site of the IGL, there is a high likelihood of anterior instability (Figs 8–10). This information may guide the orthopedic surgeon in preoperative planning and in the selection of appropriate surgical or conservative treatment. Rarely, patients develop trauma-related instability due to ligamentous stretching and laxity without an associated labral tear. MR arthrography is less valuable in these cases because the entire inferior labral-ligamentous complex appears intact. Currently, no accurate MR imaging criteria are recognized in the diagnosis of capsular laxity.

Although MR arthrographic images have demonstrated greater than 90% accuracy in the detection of anteroinferior glenoid labral tears, diagnostic confidence may be further increased when the shoulder is imaged in abduction and external rotation (ABER) (13,14). The ABER position is achieved by flexing the elbow and placing the patient’s hand posterior to the contralateral aspect of the head or neck (13). With use of a coronal localizer image, ABER images are then prescribed parallel to the long axis of the humerus. In the ABER position, the IGL is stretched, transmitting tension to the labrum. Thus, an anteroinferior glenoid labral tear that is nondisplaced when the shoulder is in a neutral position has a greater likelihood of being displaced from the glenoid rim and becoming more conspicuous when the shoulder is in the ABER position.

Hip

Most hip disorders are self-limited and respond to conservative therapy. However, a subset of patients have chronic hip pain or mechanical symptoms (with or without antecedent trauma) and nondiagnostic radiographic examinations. The socioeconomic impact can be great because these patients miss work due to disabling symptoms, seek treatment from several orthopedic surgeons,
and undergo repeated testing with conventional radiography, bone scintigraphy, computed tomography (CT), and conventional MR imaging. Eventually, arthroscopy or open surgery is performed as a combined diagnostic and therapeutic procedure.

At surgery, the acetabular labrum and hyaline cartilage are inspected for tears and focal defects, and the capsular recesses are examined for loose bodies. In this subpopulation of patients, acetabular labral tears are identified in over one-half of hips, loose bodies are removed in over one-third of hips, and chondral defects of the femoral head or acetabulum are detected in approximately one-quarter of hips (15,16). Thus, several intraarticular abnormalities are frequently detected in combination.

Preliminary investigations with hip MR arthrography have demonstrated a close correlation between imaging findings and surgical results (17). High diagnostic accuracy is achieved because contrast material outlines the labrum and cartilage and fills tears. Anatomic detail and signal-to-noise ratio are improved by imaging only one hip and by using a surface coil (eg, shoulder or cardiac coil) positioned over the femoral head. Sagittal and coronal T1-weighted images with or without fat suppression can show dysplastic changes, labral tears, and chondral defects. Sagittal oblique images, which are prescribed parallel to the femoral neck from coronal images, best depict the anterosuperior acetabular labrum, where sports-related labral tears and associated capsular defects usually occur (Fig 11). Axial T2-weighted images best depict intraarticular loose bodies.

Figure 10. Inferior labral-ligamentous tear and anterior instability. (a) On an axial T1-weighted MR arthographic image (450/18) through the inferior glenoid fossa, contrast material fills an anterior labral tear (arrow). (b) Coronal oblique fat-suppressed T1-weighted MR arthographic image (450/18) shows the IGL (white arrow) attached to the torn labrum (black arrow), which is displaced from the glenoid rim. Arthroscopic Bankart repair was performed.

Figure 11. Direct axial oblique MR arthrography of the hip. Such imaging optimizes detection of the most common sports-related acetabular labral tears (anterior and anterosuperior in location). On a midcoronal localizer image, the axial oblique sequence is prescribed perpendicular to the line drawn from the superior labrum to the transverse ligament. This line is usually oriented parallel to the long axis of the femoral neck.
The acetabular labrum shares common histologic and morphologic features with the glenoid labrum (Fig 12). In both the hip and shoulder, the labrum creates a fibrocartilaginous rim that deepens the socket of the joint and increases its surface area for articulation. Whereas the labrum of the shoulder lines the rim of the entire glenoid fossa, the labrum of the hip terminates inferiorly and merges with the transverse acetabular ligament. This ligament connects the anterior and posterior horns of the acetabular labrum. The normal labral fibrocartilage merges with the hyaline cartilage to form a single histologic entity.

Both the acetabular and glenoid labra show normal variations in size, shape, and signal intensity. They are usually triangular but can demonstrate rounding or flattening of the free margin. The labral contour is mostly smooth on MR arthrographic images but can show irregularities at the free margin and small sulci along its junction with articular cartilage. The signal intensity is low with all pulse sequences unless artificially increased on short-echo-time images due to the magic angle phenomenon.

Acetabular labral tears also share common MR arthrographic features with glenoid labral tears (Figs 13, 14). They usually begin at the junction of labral fibrocartilage and hyaline cartilage and can extend into the labral substance or propagate along the labral attachment to bone. Diagnostic specificity is increased if the labral fragment is displaced from the acetabular rim. Tear location depends on cause. Sports-related labral tears are anterosuperior on the acetabular rim. In hip dysplasia or other disorders that disrupt articular congruence (eg, slipped capital femoral epiphysis), labral tears tend to be superior (lateral) on the acetabular rim, where the labrum is susceptible to repeated impaction by the femoral head (18). MR arthrographic images may guide the hip arthroscopist by showing the lengths of labral abnormalities as well as their locations.

Acetabular labral tear may lead to the formation of an extraarticular cyst when the tear passes through the capsule, allowing leakage of joint fluid. Acetabular labral cysts communicate with the hip joint and can fill with contrast solution following intraarticular injection, similar to the periarticular cysts that develop in patients with meniscal tears in the knee and labral tears in the shoulder. They typically measure 1–2 cm in diameter but can enlarge to 3–4 cm. T2-weighted images are valuable in the demonstration of cysts that do not fill with contrast material, increasing diagnostic specificity for nondisplaced labral tear.

Acetabular labral tear is a starting point for degenerative joint disease. As the torn labral fragment becomes separated from the acetabular rim, it loses its capacity for cushioning and protecting
the adjacent articular cartilage. Loading forces across the joint are no longer distributed evenly over the entire cartilage surface. Repetitive impaction by the femoral head on the acetabulum eventually results in the development of chondral defects and progressive osteoarthritis. Therefore, the most important MR arthrographic diagnoses are labral tears, loose bodies (Fig 15), and chondral lesions that are amenable to arthroscopic débridement and repair.

**Elbow**

Saline solution with or without iodinated contrast material or gadolinium can be introduced into the elbow joint. This is useful in patients with suspected collateral ligament tears (19,20). Schwartz et al (19) have recommended fluoroscopic injection of a mixture of 3 mL of iodinated contrast material in 7 mL of saline solution. One of the authors of this article (L.S.S.) uses iodinated contrast material to localize the joint and then injects a mixture of gadolinium and saline solution for a total of up to 10 mL of fluid in the joint. The joint can be entered laterally over the radial head under fluoroscopic guidance or posterolaterally between the olecranon, humerus, and radial head. The latter method has the advantage of not involving a major structure such as the lateral collateral ligament (LCL) complex in the path of the injection.

The 20° posterior coronal oblique plane is ideal for visualizing the ulnar collateral ligament (UCL) and radial collateral ligament (RCL) (Fig 16) (21). These ligaments are thickenings of the joint capsule that can degenerate and tear.

**Figure 14.** Anterosuperior acetabular labral tear resected at arthroscopy. (a) Axial fat-suppressed T1-weighted MR arthographic image (400/15) shows displacement of a torn labral fragment (straight arrow) from the acetabular rim. High-signal-intensity contrast material extends under the periosteum (curved arrow), which has been stripped away from bone by the labrum. (b) On a sagittal T1-weighted MR arthographic image (600/15), the contrast material (arrow) separates the torn labral fragment from the underlying articular cartilage.

**Figure 15.** Intraarticular loose body. Axial fat-suppressed T2-weighted MR arthographic image (2,800/60) shows a low-signal-intensity focus in the acetabular fossa (arrow) surrounded by contrast material and located adjacent to the ligamentum teres, which attaches to the humeral head. An intraarticular loose body was removed at open surgery.
with or without injury to the overlying flexor or extensor tendons. The ligaments are well evaluated with MR arthrography. Conventional arthrography is not useful for detecting tears except in the early stages (within 24 hours) following acute rupture. Stress radiography can be used to diagnose tears of the UCL; however, additional abnormalities, which are frequently seen in association with these tears, cannot be completely assessed with this method.

**Ulnar Collateral Ligament.**—The UCL originates from the medial epicondyle and attaches to the medial aspect of the ulna. The UCL complex consists of three parts. The major ligament is the anterior oblique bundle, which is taut with extension and inserts on the ulna along the medial aspect of the coronoid process (sublime tubercle) (Fig 17). The insertion on the sublime tubercle is tight, and there should be little or no contrast material or fluid between the ligament and the sublime tubercle. The other components of the UCL complex are (a) the posterior oblique segment, which is fan-shaped, smaller, and taut with flexion, and (b) the transverse segment, which bridges the ulnar attachments of the anterior and posterior bands. The posterior oblique and transverse segments are often difficult to define at MR imaging and may even be absent. The posterior oblique segment can be better evaluated on sagittal images of the flexed elbow.

Rupture of the UCL usually occurs in the flexed elbow with valgus stress. This ligament is injured in sports that involve throwing. In contrast to medial epicondylitis, injury to the UCL in the throwing athlete can be devastating because athletic performance is hindered due to pain and altered biomechanics. One looks for increased signal intensity within and adjacent to the ligament at MR imaging. This can represent sprain, degeneration, hemorrhage, or edema due to microtears resulting from repetitive injury. A full-thickness tear manifests with interruption of the ligament (Fig 18), often accompanied by extravasation of fluid or contrast material into the surrounding soft tissues. Most tears occur in the midproximal fibers of the anterior bundle. The
injured ligament can also demonstrate thickening and irregularity, ligamentous laxity, and poor definition (22). Partial-thickness tears are diagnosed when there is focal disruption that does not extend through the full thickness of the ligament. Partial-thickness tears of the ligaments are best visualized if there is fluid or other contrast material adjacent to the ligament. This can be accomplished with MR arthrography (19,23,24). A particular type of partial-thickness tear of the anterior bundle of the UCL manifests at the insertion on the sublime tubercle. This form of partial UCL tear is described as the “T sign,” with contrast material extending medial to the tubercle (Fig 19). Lateral compartment bone contusions may be present in association with acute tears of the UCL. Overlying flexor tendon tears are also frequently seen.

Radial Collateral Ligament.—The RCL complex is weaker and thinner than the UCL complex. This ligament provides varus stability and is rarely stressed in the athlete. The anconeus muscle also contributes to joint stability. The RCL complex is variable and has three components: the RCL proper, which extends from the lateral epicondyle of the humerus to the annular ligament surrounding the radial head; the accessory collateral ligament; and the lateral UCL. The lateral UCL lies posterior to the RCL, arising from the lateral epicondyle and extending along the posterior aspect of the radius to insert on the supinator crest of the ulna (Fig 20). The lateral UCL is present in 90% of people and provides the primary restraint to varus stress. Disruption of the LCL results in the pivot shift phenomenon and posterolateral rotatory instability of the elbow (25). The RCL proper and the lateral UCL are best evaluated on coronal and axial MR images. Most tears of the lateral UCL occur at the humeral attachment. Unsuspected ruptures of the RCL may also be accompanied by tears of the common extensor tendon (Fig 21).
Synovial Folds.—MR arthrography can also demonstrate synovial folds (plicae) within the elbow joint (Fig 22) (26). A synovial fold that extends from the posterior fat pad in the elbow is a common finding. In some patients, thickened folds may cause locking. There is overlap between the thickness of symptomatic and asymptomatic folds, making clinical correlation imperative.

Knee
MR arthrography of the knee is used to evaluate residual or recurrent meniscal tears following meniscal surgery. It also has the potential to demonstrate loose bodies, synovial plicae, and osteochondral lesion stability.

Direct MR arthrography of the knee is performed by injecting up to 40 mL of diluted gadolinium into the knee joint following aspiration of any effusion. The injection can be performed without fluoroscopic guidance with use of either a medial or lateral patellofemoral approach. Images are obtained with either fat-suppressed T1-weighted or spoiled gradient-echo sequences, along with T2-weighted or short-inversion-time inversion recovery sequences.

The detection of residual or recurrent meniscal tears following meniscectomy or meniscal repair is difficult with conventional MR imaging, and many are turning to MR arthrography for this purpose. Applegate et al (27) compared findings at direct MR arthrography with those at conventional MR imaging in patients who had undergone meniscectomy with follow-up arthroscopy. Overall accuracy was 66% for conventional MR imaging compared with 88% for MR arthrography. In particular, MR arthrography was more accurate when more than 25% of the meniscus was resected. Most other authors have had similar results (28). The diagnosis of a recurrent tear is made when intraarticular gadolinium tracks into the meniscus (Fig 23). It has been suggested that, when a primary suture repair of the meniscus has been performed, one can distinguish a partially healed tear (in which gadolinium contacts only one meniscal surface) from a tear (characterized by extension of gadolinium between superior and inferior meniscal surfaces) (29). Recently, a prospective study of 104 postoperative menisci by White et al (30) showed a small incremental increase in accuracy for the detection of meniscal tear following meniscal surgery with direct MR arthrography compared with conventional MR imaging and indirect MR arthrography. However, no significant difference in diagnostic accuracy ($P > .54$) was apparent between the three techniques.

Wrist
MR arthrography is useful for evaluation of the ligaments and triangular fibrocartilage (TFC) of the wrist (31–33). It combines the advantages of arthrographic depiction of anatomic perforation with the direct visualization of marrow, cartilage, and soft tissues allowed by MR imaging and can be performed with single-, double-, or triple-compartment injection. The extrinsic ligaments will not be discussed in this article.

We favor the single-compartment radiocarpal injection technique. Approximately 4 mL of a mixture of diluted gadolinium and iodinated contrast material is injected into the wrist. This can be performed with fluoroscopy or with anatomic guidance at the MR imager (34). The wrist is exercised and videotaped when fluoroscopy is used. Coronal gradient-echo images with volume acquisition of 1-mm section thickness or less aid in precise localization of the perforations in these smaller structures. We also obtain fat-suppressed T1-weighted and fast spin-echo images in the coronal and axial planes. The normal radiocarpal arthrogram shows contrast material confined to the compartment between the proximal carpal row, radius, and ulna (Fig 24).

Intrinsic Proximal Carpal Row Ligaments.—The two most important intercarpal ligaments are the scapholunate ligament (SLL) and the lunotriquetral ligament (LTL). The SLL and LTL are crescentic or delta-shaped ligaments with at least three separate anatomic zones. The
dorsal and volar segments are composed of dense fibrous tissue with strong attachments to the adjacent carpal bones and extrinsic ligaments. The central segment of these ligaments is a thin membrane with relatively weak attachments to the adjacent carpal bones. The shape and signal intensity characteristics of the interosseous ligaments are variable. Although these ligaments usually have low signal intensity, there can be an occasional area of intermediate signal intensity that traverses the interosseous ligaments. This intermediate-signal-intensity area can be distinguished from a ligament tear because the signal intensity is not as high as that of fluid. Such a pattern of increased signal intensity on T1-weighted images and decreased signal intensity on T2-weighted images has been seen with ligament degeneration. Nonvisualization of the interosseous ligaments is a rare manifestation of SLL or LTL tear. Fluid signal intensity or diluted gadolinium that traverses the interosseous ligaments remain useful signs of ligament perforation or tear (Fig 25). The location of the tear in both anteroposterior and mediolateral directions is important. A perforation is not always symptomatic and should be correlated with clinical findings. Surface irregularity is a sign of fraying and partial tear. Perforations of the central segment of the interosseous ligaments are part of the aging process and may not produce any symptoms or instability.

**Triangular Fibrocartilage Perforations.**

The TFC is an important structure that cushions the ulnocarpal articulation and stabilizes the distal radioulnar joint. Tears of the TFC result in nonspecific pain, crepitus, and weakness and can be difficult to distinguish from other causes of ulnar wrist pain.

The TFC is a low-signal-intensity bow tie–like structure that extends radially from the intermediate-signal-intensity hyaline cartilage located at the dorsal ulnar aspect of the lunate fossa to the fovea at the base of the radial aspect of the ulnar styloid process and to the ulnar styloid process itself. The ulnar attachment is often obscured by surrounding loose vascular connective tissue, which has intermediate signal intensity. The prestyloid recess is an extension of the radiocarpal
joint, which also lies near the ulnar attachment of the TFC. Fluid in this recess produces increased signal intensity. The low-signal-intensity dorsal and volar distal radioulnar ligaments are most easily seen on sagittal and axial images. It is best to image the TFC with the forearm in neutral rotation (35).

Degeneration of the TFC is frequently seen and often asymptomatic. Progressive degeneration of the proximal surface leads to erosion, thinning, and perforation of the TFC. Degenerative perforations are more common in the thinner central portion of the TFC, whereas traumatic tears tend to occur in the radial portion. When there is degeneration of the TFC, MR imaging demonstrates intermediate signal intensity on short-echo-time images that does not increase on T2- or T2*-weighted images. Perforations of the TFC can be asymptomatic or posttraumatic and may contain high-signal-intensity fluid on T2-weighted and fat-suppressed T1-weighted MR arthrographic images (Fig 26). Some tears are partial and may extend only to the superior or inferior surface. With a traumatic TFC tear, fluid or contrast material is usually present in the distal radioulnar joint. The presence of fluid alone in this location with no gadolinium should suggest synovitis or mechanical irritation of the distal radioulnar joint.

Detection of TFC tear with conventional MR imaging alone has been investigated by several groups over the past two decades. In a study of 41 patients, Zlatkin et al (36) reported a sensitivity of 100% and a specificity of 93% compared with arthrography and a sensitivity of 89%, a specificity of 92%, and an accuracy of 90% compared with arthroscopic and arthroscopy. Golimbu et al (37) found a sensitivity of 93% and an accuracy of 95% in 20 patients with surgical correlation. Schweitzer et al (38) compared MR imaging with arthrography as a standard of reference in 15 patients with chronic wrist pain and found MR imaging to have a sensitivity, specificity, and accuracy of 72%, 94%, and 89%, respectively. In a prospective study of 77 patients, 59 of whom had tears at arthroscopy, Potter et al (39) demonstrated that high-resolution MR imaging has a sensitivity of 100%, a specificity of 90%, and an accuracy of 97%. Oneson et al (40) evaluated 56 patients who underwent arthroscopic evaluation of the TFC. In 27 patients, the TFC was intact at surgery; 27 patients had complete perforations; and two patients had partial defects. There was a 91% sensitivity for detecting central degenerative perforations, and the rate of detection of radial slitlike tears for two different observers was 100% and 86%, respectively. Sensitivity for detecting ulnar-sided avulsions was 25% and 50%, respectively, for these two observers. This suggests that ulnar-sided tears are more difficult to depict with routine MR imaging. Haims et al (41) most recently confirmed the limitations of nonarthrographic MR imaging in the diagnosis of peripheral ulnar-sided tears of the TFC. They found the sensitivity for evaluation of tears of the peripheral TFC complex to be 17%, with a specificity of 79% and an accuracy of 64%. It seems that MR arthrography may play an important role in improving sensitivity for TFC lesions, although this remains to be proved.

Ankle

MR arthrography can be used in selected cases of ankle MR imaging to assess ligamentous damage, impingement, and loose bodies. The following technique is recommended: Under fluoroscopic guidance, a 23-gauge needle is introduced with use of sterile technique into the ankle joint medial to the extensor hallucis longus muscle with a slight cranial tilt. Intraarticular needle placement is confirmed with an injection of up to 5 mL of iodinated contrast material. Subsequently, 5–7 mL of a mixture of 0.1 mL of diluted gadolinium, 20 mL of saline solution, and .3 mL of epinephrine (ratio, 1:1000) is injected. Thin-section (≤1-mm) three-dimensional volume spoiled gradient-echo or fat-suppressed T1-weighted images are obtained in all three planes (axial, sagittal, coronal), followed by either fat-suppressed fast spin-echo proton-density–weighted, T2-weighted, or short-inversion-time inversion recovery images in at least two planes. The examination can be made shorter by tailoring the planes and sequences to the particular problem. A normal MR arthrogram of the ankle may be associated with contrast material that enters the flexor hallucis longus and

Figure 26. Triangular fibrocartilage perforation. Coronal fat-suppressed gradient-echo MR arthrographic image shows a small perforation filled with high-signal-intensity diluted gadolinium (arrow).
flexor digitorum longus tendon sheaths as well as the subtalar joint in up to 25% of cases (42).

Ankle Ligaments.—Sprains of the LCL complex typically follow an inversion injury and are one of the most common musculoskeletal injuries, comprising up to 10% of all injuries treated in emergency departments in the United States and 15%–25% of all sports injuries (43). Although most ankle inversion injuries are self-limited, 10%–20% of patients may develop chronic lateral instability (44). Surgical repair is considered for grade III sprains, high-level athletes, and patients with chronic pain and instability (44). In all of these cases, MR arthrography might prove beneficial.

MR arthrography better demonstrates the ligaments than does conventional MR imaging, as shown in several studies, including one that looked at normal ligaments in cadavers (45). In one study, conventional MR imaging had a sensitivity of 50% for diagnosing tears of either the anterior talofibular ligament (ATL) or calcaneofibular ligament (CFL), whereas MR arthrography had a sensitivity of 100% for ATL tears and of 90% for CFL tears. In subacute and chronic cases, fluid is often absent, and MR arthrography is helpful for assessing ligamentous damage (43,46).

When injury occurs to the lateral ankle joint, the weaker ATL is torn first and most frequently. Half of all ATL tears occur at the talar insertion, and most of the others are located in the midsubstance. The CFL may be injured with more severe inversion and is almost always associated with an ATL injury. The CFL is disrupted in up to 20% of all LCL tears (42). Patients with complete disruption of the CFL are at risk for developing chronic instability. Posterior talofibular ligament injury is uncommon and is seen in combination with injury to both the ATL and CFL.

In first-degree ligament sprains, a focal area of high signal intensity is seen within the ligament on T2-weighted MR images. Contrast material does not enter the ligament. Second-degree sprains demonstrate partial discontinuity of the ligament, irregularity, beading, or fraying. Third-degree sprains manifest as discontinuity or absence of the ligament with passage of contrast material or fluid through the ligamentous disruption into the surrounding soft tissues (Fig 25). Chronically injured ligaments may also appear wavy or thickened at MR imaging.

An ATL tear manifests as nonvisualization or extravasation of contrast material anteriorly through a defect in the ligament. A CFL tear is evident when there is contrast material lateral to the ligament or in the peroneal tendon sheaths (Fig 27). Extravasation of contrast material into the soft tissue behind the posterior talofibular ligament (PTL) indicates a tear of this structure. In a cadaver study, MR arthrography was not shown to be more sensitive or specific than conventional MR imaging for evaluation of the medial collateral ligament complex (45).

The anterior talofibular ligament complex extends from the longitudinal tubercle located on the anterior border of the lateral malleolus to the anterolateral tubercle of the tibia. The posterior talofibular ligament complex extends from the posterolateral tibial tubercle to the posterior and distal aspect of the lateral malleolus. A deep transverse ligamentous component is located inferiorly. The third component of the posterior talofibular ligament complex is the posterior intermalleolar ligament (47). It extends between the posterior aspect of the medial and lateral malleoli and is often not visualized on MR imaging examinations. The interosseous ligament is located at the most caudal end of the interosseous membrane. It is approximately 1 cm high and has a globular configuration. The intermalleolar ligament is known to cause posterior impingement in ballet dancers (47). MR arthrography improves visualization of the tibiofibular and intermalleolar ligaments (45). Posterior ligaments are best seen with the ankle in dorsiflexion, and subsequent plantar flexion demonstrates impingement. Potential pitfalls of MR arthrography of the ankle ligaments include accumulation of contrast material in the anterior and posterior recesses of the
ankle joint, which manifests as smooth, encapsulated fluid outside of these ligaments. The bulbous appearance of the PTL and posterior tibiofibular ligament on sagittal images can simulate loose bodies. Serial evaluation of sagittal images and knowledge of the characteristic location of these ligaments help avoid this pitfall.

Ankle Impingement Syndromes.—Ankle impingement is a clinical diagnosis. At times, MR arthrography is useful for demonstrating anterolateral, anteromedial, and posterior impingement syndromes in the ankle because it is the most accurate means of assessing the capsular recesses of the ankle (48,49).

The anterolateral recess of the tibiotalar joint is a site of repeated microtrauma and hemorrhage from forced plantar flexion and supination of the ankle. Hypertrophy of the inferior portion of the ATL and osseous spurs can also contribute to this form of impingement. This can result in synovial scarring, inflammation, and hypertrophy, which produce symptoms that are relieved with physical therapy and débridement. The characteristic appearance of this form of impingement is nodular capsular thickening or a low-signal-intensity mass in the lateral gutter bounded posteromedially by the tibia, laterally by the fibula, and anteriorly and posteriorly by the tibiotalar joint capsule and ligaments (Fig 28). Absence of fluid between the anterolateral soft tissues and the anterior surface of the fibula is invariably associated with scarring and synovitis. However, findings should be correlated with clinical signs of impingement because a substantial number of asymptomatic ankles have similar appearances (48).

Anteromedial ankle impingement syndrome is generally thought to result from supination (inversion) injury. An anteromedial synovial mass or synovial thickening is well seen when there is fluid in the joint. There may also be associated tibial or talus osteophytes.

Posterior impingement has been described following forced plantar flexion with compression of the osseous and soft tissues between the calcaneus and tibia, including the intermalleolar ligament (47).

Osteochondral Injuries
The medial femoral condyle, talar dome, and capitellum are frequent sites of osteochondral injury. Treatment is based on the degree of stability of the osteochondral fragment. If the fragment is attached to bone, the joint is managed conservatively. If there is partial or complete detachment, the fragment is either removed or reattached (pinned) to the parent bone. MR arthrography is helpful in evaluating the articular cartilage, and partial or complete loosening of the fragment manifests as contrast material entering the fragment–parent bone interface (Fig 29). In one study, MR arthrography had a sensitivity of 85% in the detection of osteochondral lesions, compared with a 69% sensitivity for conventional MR imaging (50). MR arthrography had an accuracy of 93% in the evaluation of instability, compared with a 39% accuracy for conventional MR imaging.

Intraarticular Osteochondral Bodies
CT arthrography is very useful for identifying loose bodies. However, it is less capable of detecting other abnormalities in the joint, such as a cartilaginous donor site or associated ligamentous damage, so that one may prefer to go directly to MR arthrography for delineation of loose cartilage and bone in the joint (Fig 15) (46). Gadolinium-enhanced MR arthrography has demonstrated a high accuracy in the detection of osseous and cartilaginous bodies combined (92%) and was significantly better than MR imaging (57%-70% accuracy) in this setting (51). Air bubbles can mimic loose bodies at MR arthrography, but most air bubbles can be distinguished by their nondependent position and typical appearance.

Indirect MR Arthrography
Indirect MR arthrography is predicated on the concept that contrast material injected intravenously over time will diffuse into the joint space, so that quasiarthrographic T1-weighted images...
can be obtained (52). It is helpful to use a fluid compartment model to understand the physiologic foundations of indirect MR arthrography (53). MR imaging contrast agents have variable degrees of weak protein binding. Consequently, most contrast agents can be thought of as existing in the plasma compartment. Another compartment is the interstitial space, which exists in the soft tissues within and between organs. There is normally little movement from the plasma compartment into the interstitial space because in most of the body there is a tight basement membrane in the walls of the blood vessels. Last and most important, for indirect MR arthrography there is another compartment: the joint space. The joint space normally contains small but variable amounts of synovial fluid (54). Because the blood vessels in the synovial membrane lack a basement membrane, the synovial fluid is equivalent to lightly filtrated plasma. Consequently, a fairly rapid steady state develops in which substances develop equal concentrations in plasma as in the joint fluid (53).

MR imaging contrast agents do not produce signal themselves but affect the relaxivity of the surrounding structures; consequently, a very low concentration can affect numerous surrounding molecules. After a period of time, the contrast material that has diffused into the joint space will have a signal intensity similar to that of contrast material injected directly into the joint space (55).

There are two physical processes that cause contrast material to move into the joint space: bulk flow and diffusion (53). Bulk flow is related to the pressure gradient from the vascular system into the joint space. Because the joint spaces are low-resistance structures, with the contrast material in the arterial system or even the venous system, there is almost always a pressure gradient from the plasma. Pathophysiologic processes that act to increase intraarticular pressure will decrease the amount and rate of bulk flow. The most important of these processes are either tense effusions or effusions with high viscosity. The former occur with hemorrhagic effusions following trauma or in septic arthritis; the latter occur with arthritic diseases or chronic infections. These conditions will decrease the indirect arthrographic effect and prolong the time interval until a steady state occurs between the vascular compartment and the joint compartment. To some degree, exercise will also increase intraarticular pressure, and although it has other positive effects on indirect arthrographic images, it has the negative effect of decreasing bulk flow (56). However, if exercise is passive, the intraarticular pressure does not increase and there is little negative effect on bulk flow (53). Passive exercise is done by the contralateral extremity moving the ipsilateral extremity without muscle contraction of the extremity to be imaged. Exercise, specifically active exercise, increases vascular pressure, thereby improving bulk flow into the joint (57). Therefore, both passive and active exercise can accentuate the indirect arthrographic effect by means of slightly different processes. Interestingly, anxiety, by increasing arterial pressure, theoretically should increase bulk flow and, consequently, the indirect arthrographic effect.

Diffusion is based on the difference in concentration between plasma and joint fluid (58). One way of increasing the diffusion gradient is to increase the dose of contrast material administered intravenously, and, thus, the plasma concentration. Double- and triple-dose intravenous injections have a positive effect on indirect arthrography but not nearly as much as one might think (59). Exercise decreases the perisynovial concentration of the joint fluid by moving joint fluid away from the membrane, thereby increasing the concentration gradient. This is another important positive effect of exercise on indirect MR arthrography.

Contrast agents that have high relaxivity, particularly when placed in a proteinaceous environment, have the most prominent indirect effect. This differs from the relaxivity required for intravenous use, which is measured in a saline environment. In addition, the weaker the protein binding of the agent, the greater the diffusion and the greater the indirect effect. Lastly, the ionicity of these agents leads to positive secondary effects. Specifically, highly charged agents will bind to proteoglycans in cartilage, providing additional information on early cartilage loss (60). Therefore, the ideal contrast agent with indirect MR
arthrography is weakly protein-based, highly charged, and has high relaxivity in a proteinaceous environment.

Indirect MR arthrography generally works best in joints that have the bulk of the joint fluid in proximity to the synovial membrane. Such joints are small or have large amounts of synovial invagination. Consequently, indirect MR arthrography works best in the wrist, ankle, fingers, and toes because these joints are small, or in the shoulder, which has a fair amount of synovial invagination (Figs 30, 31) (61–68). Indirect arthrography is not as successful in joints that have a large distance for the contrast material to diffuse across, most prominently the knee (Fig 32) (57,69).

In the interpretation of indirect MR arthrographic images, it is important to understand the differences between indirect and direct MR arthrography. The most important difference is that contrast enhancement is not affected by compartmental anatomy at indirect MR arthrography; every joint space will enhance (53). Consequently, contrast material in the subacromial-subdeltoid bursa enhances and may be seen regardless of whether a rotator cuff tear is present (Fig 33). However, one may use the enhancement relative to a standard of reference as a window into the vascularity of that structure. Hyperemia related to disease will cause an articulation to enhance more quickly and intensely and is usually an indication of an internal derangement or some other type of pathologic process affecting the joint (Fig 34) (62). Joints that opacify slowly may have fibrotic synovium or viscous effusions (Fig 32). This information based on differential enhancement is an advantage of indirect MR arthrography.

Another difference between indirect and direct MR arthrography is that every abnormality or
vascularized structure will enhance with the indirect method. This includes not only joint effusions, but also abnormal marrow, tendons, or cartilage (Fig 35) (59). Consequently, a rotator cuff tear will directly enhance from the hyperemic blood flow (Fig 33) and indirectly enhance through contrast material imbibition into the defect from the joint fluid. However, this is a diagnostic disadvantage in the shoulder because tendinosis enhancement limits the conspicuity of rotator cuff tears (Fig 36) (65).

Most extraarticular pathologic processes will also enhance to some degree. These include plan-
indirect MR arthrography due to enhancement of the subchondral bone related to trabecular disruption and hyperemia and visualization of enhanced fluid filling the defect (Fig 34). Bone bruises, geodes, and inflammatory erosions from arthritis also enhance prominently. However, some articular and extraarticular pathologic processes do not enhance. The most important of these are meniscal tears, which may not be visible without significantly delayed images because imbibition is required for diagnosis (30).

The most important advantages of indirect MR arthrography are logistic. No fluoroscopic guidance is required, there is no articular injection, and imaging can be performed during off-hours or offsite. In addition, the normal concerns about scheduling MR imaging shortly after injection do not apply to indirect MR arthrography. These all represent significant advantages of indirect MR arthrography over direct MR arthrography. However, there are some disadvantages with indirect MR arthrography. One is related to the direct vascular effect of intravenous contrast material used for indirect arthrography. This becomes a clinical problem in structures in which contrast enhancement is seen, not as a sign of disease, but of normal vascularity. These vascularized structures include the periphery of the menisci and of the TFC (Fig 37) (41). Both of these structures can be difficult to evaluate on unenhanced images, but evaluation becomes even more difficult on enhanced images. In addition, structures that depend on distention for visualization—in particular, the labrum—are poorly seen (67). With direct MR arthrography, distention is predictable; with indirect MR arthrography, visualization depends on the presence and size of the effusions (Fig 38) (53). As discussed earlier, most of the spectrum of disorders will enhance at indirect MR arthrography, not just the “tears.” This may make the more severe stages of disease less conspicuous against the background enhancement. This occurs in the shoulder (rotator cuff) as previously discussed as well as in the labrum.

Technically, indirect MR arthrography involves protocol considerations similar to those of direct arthrography, with T1-weighted images, often with fat suppression, obtained in multiple planes. These T1-weighted images can be obtained with conventional spin-echo, fast spin-echo, or gradient-echo sequences (either three-dimensional or multisection) (Fig 39). As with direct MR arthrography, T2-weighted imaging is suggested in a plane that allows optimal visualization of extraarticular disease. There are, however, two important differences between indirect and
direct MR arthrography in terms of imaging protocol. One is that fat suppression is almost mandatory in indirect MR arthrography. Because the concentration of the contrast agents in the joint fluid is so low, they may be quite difficult to visualize without fat suppression. The second protocol-related consideration is the concept of biphasic indirect MR arthrography.

Biphasic indirect arthrography takes advantage of the fact that the gadolinium-based agents are vascular agents. Consequently, vascular information can be gleaned and direct enhancement of the pathologic processes discussed earlier can be seen. Therefore, we often obtain an initial T1-weighted image immediately following contrast material administration (Fig 40a). These early images are the vascular images. T2-weighted imaging is used to visualize extraarticular disease. This is followed by “delayed” fat-suppressed T1-weighted imaging performed in three planes. These final sets of images are the indirect MR arthrographic images (Fig 40b). Thus, two sets of T1-weighted images (early and late) are obtained; hence the term biphasic. This technique can only be used without patient exercise.

Overall, exercise tends to improve the indirect effect. The patient undergoes injection in the waiting area or a staging area, and the contrast material subsequently diffuses. It is our opinion that in this situation, images obtained prior to contrast material administration are not worth the logistic difficulties. Exercise can be passive or active, each with its own advantages as discussed earlier. However, it is not necessary for the patient to exercise for more than 10 minutes (70).
Imaging should be delayed when the traditional indirect MR arthrographic technique (as opposed to the biphasic technique) is used (53). General guidelines for the delay time are 5–10 minutes in the wrist, elbow, or ankle; 15 minutes in the shoulder and hip; and at least 30 minutes in the knee. If there is hyperemia or synovitis of the structure of interest, these times can be decreased by one-half. However, if there is clinically suspected joint effusion, particularly tense effusion, the time should be at least doubled.

Indirect arthrography is also useful in postoperative situations, similar to those situations in which one would use direct MR arthrography. The one time that indirect MR arthrography is not recommended is for labral tears, particularly in the shoulder but also in the hip, although to a lesser degree. For this indication, distention of the joint is necessary for the contrast material to dissect between small tears or detachments of the labrum.

In our opinion, the overall advantage of indirect MR arthrography lies in gathering combined intraarticular and physiologic information, especially in the wrist, foot, ankle, and elbow (Fig 41). Indirect MR arthrography can be used effectively in the knee. However, the biphasic technique cannot be used because it takes longer for the contrast material to diffuse into the knee due to the large, or potentially large, joint volume. Because there is no control of articular distention as with direct MR arthrography, it is hard to anticipate how much time should transpire before obtaining delayed images.

The most important indication for indirect MR arthrography is the need for detailed evaluation of intra- and extraarticular disease in any joint. Indirect MR arthrography can be used to rule in or diagnose abnormalities as well as to exclude abnormalities. If a structure with questionable clinical features does not enhance, it is almost invariably normal, and therefore disease in this region can be excluded with confidence.

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