The Role of MR Imaging in Avascular Necrosis of the Femoral Head

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ABSTRACT

Due to the pattern of its blood supply, the femoral head is particularly vulnerable to avascular necrosis (AVN). Nontraumatic AVN is a devastating disorder affecting young patients, and despite treatment it normally follows a progressive course toward a destructive osteoarthropathy. Magnetic resonance (MR) imaging is currently used in major classification systems solely for early detection of femoral head AVN when plain radiographs are normal. More recent data have shown that MR imaging may improve staging, investigate radiologically occult collapse, depict other causes of disability and pain, assess prognosis, and evaluate treatment. This article reviews the established and evolving role of MR imaging in patients at risk or with known femoral head AVN.

KEYWORDS: MR imaging/diagnosis, hip joint, osteonecrosis, avascular necrosis, bone marrow/ischemia, vascularized grafts/osteonecrosis

Osteonecrosis or avascular necrosis (AVN) of the femoral head is an increasingly common disease, affecting up to 20,000 new patients and leading to as many as 12% of total hip arthroplasties per year in the United States.¹ The disease affects mainly young men at their late 30s and early 40s, is characterized by non-specific symptoms, and is initially unilateral with progression to bilateral femoral head involvement in up to 72% of patients.²

AVN is a result of irreversible anoxia of the affected subchondral bone, resulting in death of osteocytes and compensatory osteoblastic activity at the adjacent viable bone.³ Mechanical instability may cause failure of the subchondral trabeculae and articular collapse. The ischemic insult may be associated with an apparent etiologic/risk factor (secondary AVN) or may have no identified etiology (primary AVN).⁴ There is an extensive list of pathological conditions and risk factors associated with AVN, including trauma, hypercoagulation disorders, lipid storage diseases, autoimmune/collagen diseases, hypercortisolism, dyslipidemia, smoking, alcoholism, hemodialysis, transplantation, and radiation.⁴ Trauma may mechanically disrupt blood supply to the femoral head. In nontraumatic cases, although susceptibility genes have been identified, the pathological process is less well defined and the disease is considered multifactorial.⁵,⁶

If left untreated, the disease progresses in 80% of cases and eventually requires total hip arthroplasty.⁷ The result of surgical treatment is determined largely by the stage of the disease when it is first depicted. Because treatment at an early stage is directly associated with better prognosis, early diagnosis and accurate staging of AVN is crucial.¹,⁸

Magnetic resonance (MR) imaging is highly sensitive in depicting early AVN and is considered the method of choice for accurate diagnosis and staging of the disease.⁹–¹³ MR imaging can also assess severity and...
prognosis, depict the presence of multiple foci of involvement, and guide and follow up the surgical treatment.\textsuperscript{4} MR imaging is also used for the detection of minimal AVN lesions\textsuperscript{14,15} and for the prompt diagnosis and follow-up in Legg-Calvé-Perthes (LCP) disease.\textsuperscript{16}

This article reviews the established and evolving knowledge on MR imaging strategies and their role in the diagnosis and management of AVN of the hip.

**MAGNETIC RESONANCE IMAGING PROTOCOL FOR THE DETECTION OF AVASCULAR NECROSIS**

A basic MR imaging examination protocol for suspected AVN includes coronal T1-weighted spin-echo (SE) and coronal short tau inversion recovery (STIR) or fat-suppressed proton-density (PD)/T2-weighted fast (turbo spin-echo [TSE]) sequences with large fields of view. In case of femoral head marrow abnormalities, small fields of view on either side with fat-suppressed PD/T2-weighted and cartilage-specific sequences should be used and tailored to multiple planes, the axial oblique being more useful for the evaluation of the anterosuperior surface.

The use of intravenous contrast administration shows decreased enhancement in the necrotic bone and increased enhancement at the reparative interface and has been suggested as a means to differentiate viable from necrotic tissue.\textsuperscript{17,18} However, this differentiation can be performed without using contrast medium because viable tissue exhibits low signal intensity on T1-weighted and intermediate or high on STIR and fat-suppressed PD/T2-weighted, whereas necrotic areas are hypointense on all sequences.\textsuperscript{3} However, contrast enhancement can be valuable for increasing signal-to-noise ratio and providing images with increased special resolution as well as for preoperative evaluation of the femoral head contour, for monitoring a vascularized graft, and for early diagnosis of LCP disease.\textsuperscript{3,16}

**MAGNETIC RESONANCE IMAGING OF FEMORAL HEAD AVASCULAR NECROSIS**

The presence of a circumscribed subchondral “band-like” lesion with low signal intensity (SI) on T1-weighted sequences is considered pathognomonic of AVN (Fig. 1).\textsuperscript{19} The “double-line” sign seen on non-fat-suppressed T2-weighted SE and TSE images is virtually diagnostic of AVN. It occurs at the interface between viable and nonviable tissue and consists of an outer low SI rim (suggested to represent reactive sclerotic bone) and an inner high SI rim (considered to represent vascular granulation tissue and/or chondroid metaplasia). It was first described by Mitchell et al, who found this sign in 80% of AVN lesions.\textsuperscript{20} According to the SI of the region within the double line and based on the chronological order of its appearance, Mitchell et al proposed a classification system ranging from A (early stage, retaining normal fat SI) to D (advanced stage, low SI due to fibrous tissue and sclerosis). This system has not been used widely because it does not correlate with radiographic staging and prognosis.

Besides its definite association with histopathological changes, the “double-line” sign is considered to reflect a chemical shift artifact notified at the frequency encoding direction axis of the field (Fig. 2).\textsuperscript{4,19–23} Although the double-line sign has the characteristics of an artifact, this does not alter its diagnostic significance. Nowadays, there is widespread use of T2-weighted TSE sequences with spectral fat noise ratio and providing images with increased special resolution as well as for preoperative evaluation of the femoral head contour, for monitoring a vascularized graft, and for early diagnosis of LCP disease.\textsuperscript{3,16}

**Figure 1** Asymptomatic 45-year-old male patient with avascular necrosis, stage ARCO I. (A) Plain radiograph is normal. (B) Coronal T1-weighted magnetic resonance image shows the “band-like” sign, which is typical of avascular necrosis (arrows).
saturation (to overcome the JJ-coupling effect that leads to bright fat) and thus, the double-line sign is not seen but rather manifests as a “bright band-like” sign evident also on contrast-enhanced T1-weighted sequences (Figs. 3 and 4).4

Subchondral fractures in AVN typically occur as low SI lines on T1-weighted MR images and can be differentiated from subchondral insufficiency fractures in osteoporotic women based on the shape of the lesion: In AVN, the low SI band is smooth, concave to articular surface, and circumscribes all of the necrotic segment, whereas in insufficiency fractures the low SI band is irregular, discontinuous, and convex to the articular surface.24,25 On T2-weighted SE MR images, subchondral fractures may have a variable SI because the fracture may be filled by gas or fluid (Figs. 3 and 5).26 MR imaging has been found to be less sensitive than computed tomography (CT) in detecting subchondral fractures in AVN: Extension of the fracture line through the cortex in CT is seen in 63% of patients who do not show any evidence of fracture with MR.3,26 In our experience (unpublished data), modern MR scanners in the appropriate protocol setting including unilateral two-dimensional and/or three-dimensional high-resolution images, are able to demonstrate the subchondral fracture equally or even better than CT, the latter being limited from the radiation it induces.

Joint effusion, probably secondary to AVN-related synovitis, is seen in 58 to 72% of patients with AVN regardless of the presence of articular collapse (Figs. 3 and 5).27,28 Joint effusion is usually found in association with bone marrow edema and is more common (92%) in advanced disease.28

**EARLY DIAGNOSIS AND MAGNETIC RESONANCE IMAGING**

MR imaging has been shown to be more sensitive than CT or scintigraphy for early detection of AVN in patients with normal radiographs (stage I) (Fig. 1). The reported sensitivity of MRI for early diagnosis of AVN ranges between 88% and 100% compared with 81% of radionuclide scintigraphy.9,12,13,29 In one study, MR imaging detected AVN in 25% of hips in the preradiological stage (stage I).30 In another study it was found that 88% of asymptomatic and radiographically normal hips had early stage focal lesions evident on MR imaging.12 Even limited MR imaging protocols can effectively diagnose the presence and quantify the size of AVN.31

MR imaging can also be helpful for the prediction and early detection of AVN in patients with predisposing factors, such as hip trauma. MR studies can detect signs suggesting AVN in up to 57% of patients at 3 months following simple hip dislocation.32,33 MR imaging with and without contrast is suggested in the follow-up of hip dislocation in patients with worsening of pain upon resumption of normal activities (Fig. 6). Dynamic MRI has been shown to be highly reliable in the evaluation of femoral head vascularity and progression to AVN after intracapsular femoral neck fracture.34 Preliminary studies have shown that proton MR spectroscopy can detect changes in the lipid/water spectra of patients at risk of AVN before any morphological changes are evident, thus suggesting a potential role of this technique in predicting the risk of developing AVN.35 Increased diffusion of water protons has been also found in hips with AVN compared with normal
Figure 3  A 27-year-old male patient with a history of alcohol abuse and painful hip joints. (A) Coronal T1-weighted magnetic resonance (MR) image shows bilateral “band-like” sign, typical of avascular necrosis (arrows). (B) Axial T2-weighted turbo spin-echo MR image shows bilateral “double-line” sign (small open arrows) and in addition a subchondral fracture on the left (large open arrow). The axial oblique high-resolution fat-suppressed contrast-enhanced T1-weighted MR images of the (C) right hip and (D) left hip show the “bright band-like” sign (arrows). Synovium enhancement and joint effusion is also seen bilaterally.

Figure 4  Same patient as in Fig. 1. (A) Coronal fat-suppressed T2-weighted and (B) axial oblique fat-suppressed contrast-enhanced T1-weighted magnetic resonance images demonstrate the “bright band-like” sign anterosuperiorly (arrows). No bone marrow edema is depicted in this asymptomatic patient.
Figure 5  A symptomatic patient with known femoral head avascular necrosis. (A) The plain anteroposterior radiograph shows a lytic region surrounded by sclerosis (arrows) suggesting an ARCO II stage lesion. (B) The sagittal short tau inversion recovery magnetic resonance (MR) image shows diffuse bone marrow edema within the femoral head and a subchondral fracture (open arrow). (C) The coronal T2-weighted MR image shows the osteonecrotic area (black arrows) and the subchondral fracture.

Figure 6  A patient who sustained an avulsion of the round ligament of the right hip 4 months before imaging following a posterior hip dislocation during a motor vehicle accident. (A) Coronal T1-weighted magnetic resonance (MR) image shows reduced signal intensity of the right femoral head epiphysis (arrow). (B) Axial fat-suppressed contrast-enhanced T1-weighted MR image shows the typical for avascular necrosis “bright band-like” sign that surrounds the ischemic low signal intensity area (arrow).
Proton MR spectroscopy and diffusion-weighted imaging (DWI) are not yet in routine use for musculoskeletal imaging, and thus their role for early detection of AVN remains to be clarified.

**ACCURATE CLASSIFICATION/STAGING**

MR is currently an integral part of several staging systems and has been used as a separate tool for lesion classification and lesion size quantification. There are various grading and classification systems incorporating a variety of methods for lesion quantification because there is no agreement yet on a single universal system. However, the most frequently used systems are those from University of Pennsylvania (Steinberg’s) and the Association Research Circulation Osseous (ARCO) classification. The first classification system to incorporate MR was that of the University of Pennsylvania. The stage in this system is determined initially according to the changes seen on radiography and MR and then based on measurements of lesion size and articular surface involvement. Later, for simplification reasons, stages II and IV and stages V and VI were combined to provide a total of five rather than seven stages (ARCO international classification system).

The most critical point in all the classification systems is the loss of spherical contour of the femoral head. Although MR is used at the early precollapse stages, only radiographs are employed routinely for the evaluation of collapse, and MR is used only in the precollapse stages. It has been shown that plain radiographs can miss important information in stages II and III, because they overestimate stage II, underestimate stage III lesions, and are inaccurate in estimating the collapse size, which is an important parameter in therapeutic decisions (Figs. 7 and 8). Therefore it has been suggested that the wider use of MR imaging findings in any classification system could improve the accuracy and prognostic value by means of discriminating between early and advanced stages. Others found that MR is less sensitive than CT in detecting subchondral fractures (stage III disease). This remains to be confirmed by additional studies.

**BONE MARROW EDEMA AND AVASCULAR NECROSIS**

Bone marrow edema (BME) may be seen in 30 to 50% of hips with AVN of hip. It is located within the femoral head, neck, and intertrochanteric region and is probably a reaction to subchondral fracture and blockage of venous drainage. Distinction between irreversible AVN-related BME and reversible BME associated with transient osteoporosis of hip (TOH) is important because AVN requires early diagnosis and joint-preserving treatment, whereas TOH is self-limiting and requires no specific treatment. The absence of subchondral abnormalities almost always corresponds to TOH. Other findings suggesting AVN-related BME include bilateral involvement and the "double-line" and "bright band-like" signs. On the contrary, TOH is almost always unilateral, and if subchondral lesions exist, these are thin and short, probably corresponding to insufficiency fractures. In TOH there is delayed and diffuse contrast enhancement up to subchondral bone, whereas in AVN the necrotic area does not enhance. DWI does not aid in the differential diagnosis, since there is increased diffusion in all cases.

The association of BME with AVN has been controversial. BME was initially considered to represent the early stage of the disease, followed by development of focal lesions typical of AVN. It was later shown that

![Figure 7](image-url) Radiographic understaging of femoral head osteonecrosis. (A) Frog plain radiograph shows sclerosis and lysis in a symptomatic patient, with intact femoral head suggesting a stage ARCO II disease. The contrast-enhanced fat-suppressed T1-weighted magnetic resonance images in the (B) sagittal and (C) oblique axial planes confirm the presence of the osteonecrotic lesion (thin arrows) and in addition show bone marrow edema (open arrows). It is only the oblique axial image, which in addition shows a focal flattening of the femoral head (arrowhead, C), thus upgrading the stage to IIIA.
BME is never found at the early stages before the appearance of the “band-like” sign, which is the initial change of AVN.42,43,50,51 Further studies showed that BME develops after the onset or worsening of pain,43,52 is typically identified in advanced (stage III) disease,28,42,43 and it correlates with necrotic volume43 and articular collapse43 (Figs. 9 and 10).

Regarding the effect of surgical treatment, it has been shown that the presence of BME is associated with failure of core decompression and progression to degenerative arthritis requiring total hip arthroplasty.53 In the postoperative setting, BME has been found after failure of vascularized bone grafting and femoral head collapse48 (Fig. 11).

Thus BME of the femoral head in the presence of discrete “band-like” subchondral lesions suggests the diagnosis of AVN and should be considered a poor prognostic sign in the course of the disease.

MAGNETIC RESONANCE FINDINGS IN RELATION TO PAIN
Disabling pain may appear in various stages of AVN, even in the absence of articular collapse. The cause of pain is not well understood, and possible contributing factors include elevated intramedullary pressure and development of subchondral fracture.28 Several MRI studies has shown the presence of a close relationship between pain and BME, necrotic volume, and joint effusion (Figs. 3 and 9).28,41–43,52

It has been shown that pain is rare in stages I and II and is commonly encountered in stage III of the disease,28,42 suggesting the relationship between pain, subchondral fracture, and BME (Figs. 3, 5, and 10). BME has been found to be the most important prognostic factor for onset or worsening of hip pain.43,52 This finding is also confirmed by the fact that hip pain is 13 times more likely when BME is present.28 Hip pain may subside after core decompression with the resolution of intramedullary hypertension and BME or occasionally spontaneously with conservative management.41 Hip pain also correlates to the necrotic volume, with large necrotic volume being the second useful indicator for predicting future worsening of pain.28,52 Although the association of joint effusion with pain is controversial, BME was found to be 16 times more likely to occur when there was a joint effusion, thus showing that the painful effect of BME may be enhanced in the presence of joint effusion.28,41

AVN does not always produce pain. Hips with stage I and II disease may be completely asymptomatic (Fig. 1).28 Clinically occult AVN has also been reported in patients with the presence of a “band-like” pattern at 14 weeks from the onset of steroid therapy43 as well as in 6% of patients undergoing a renal transplant and steroid therapy.54

Figure 8 A 51-year-old male patient with a history of carcinoma of the larynx and corticosteroid administration. The patient was referred for magnetic resonance (MR) imaging because of a persistent pain for the last 3 months over the left hip and joint movement restriction. (A) Plain radiograph shows osteosclerosis (arrows) typical for avascular necrosis (AVN) of the femoral head (stage ARCO II). (B) Coronal T1-weighted MR image confirms the presence of AVN (arrow). (C) Oblique axial fat-suppressed contrast-enhanced high-resolution T1-weighted MR image shows depression of the articular surface (open arrows). This finding upgrades the stage to ARCO IIIA. There is also bone marrow edema secondary to the articular collapse (arrows).
Figure 9 A previously healthy 48-year-old male patient, without any predisposing factor for avascular necrosis, presents with a left hip pain of 6-month duration. (A) Plain radiographs are unremarkable. (B) Sagittal T1-weighted magnetic resonance (MR) images of the (B) right and (C) left femoral heads show the typical “band-like” sign of the osteonecrotic lesions (black arrows). On the left (C) there is also a low signal intensity area suggesting bone marrow edema (asterisk). (D) Coronal short tau inversion recovery MR image confirms the presence of extensive bone marrow edema on the left (asterisk).

Figure 10 A 50-year-old female patient with bilateral avascular necrosis and pain only on the right side. (A) Coronal T1-weighted magnetic resonance (MR) image shows the osteonecrotic lesions (arrows). (B) Coronal short tau inversion recovery MR image demonstrates bone marrow edema (long arrow) and a subchondral fracture (short arrow) in addition. (C) Oblique axial T2* MR image confirms the presence of the subchondral fracture (arrow). (D) Surgical specimen of the femoral head following total hip arthroplasty 3 years after imaging, due to persistent pain and deteriorating functional limitation, shows the extensive fracture and delamination of the chondral plate (arrows).
MR imaging may be extremely helpful in patients with predisposing factors for AVN and hip joint pain. It can accurately confirm or rule out AVN, and in addition it is able to investigate other causes of pain such as femoroacetabular impingement, an enlarging herniation pit due to long-standing effusion and bursitis (Figs. 12–14).

MAGNETIC RESONANCE IMAGING FOR ASSESSMENT OF PROGNOSIS AND REPAIR PROCESS

The lesion size and extent of femoral head involvement have been found to be the main factor in predicting outcome and determining treatment in AVN. The size of lesions on plain radiographs may be difficult to assess and might not correlate with the size on MRI, so the use of radiographs has not been widely applied. Several studies have shown that the extent of medium and large necrotic lesions in MR imaging can predict the risk of femoral head collapse. There are various methods of measuring the lesion size using MR imaging, varying from simple quantitative or visual methods to sophisticated ones requiring advanced software. The extent of femoral head involvement can be estimated as the percentage of the weightbearing area, index of necrotic extent, and absolute necrotic volume. The lesion location is also an important parameter in predicting femoral head collapse. It has been shown using volume analysis and classification that the posteroinferior location and medial two thirds extending to the acetabular ridge are more commonly associated with deterioration. Two reproducible and simple methods not requiring sophisticated software tools are based on evaluating the coronal and sagittal MR images using conventional sequences (Figs. 15 and 16).
MR imaging may be of value for long-term assessment of lesion size and progress of the repair process. Several studies have shown that small early lesions in stage I can undergo reduction in volume by at least 15% on T1-weighted MR images or even spontaneous resolution with corticosteroid therapy over the course of a few years. The reduction in volume observed in MR images is a slow, discontinuous, and time-dependent process. It has also been shown that the repair process at the periphery of AVN (manifested as the band-like pattern on T1-weighted images) does not progress unless collapse has occurred.

**MONITORING OF SURGICAL TREATMENT**

MR imaging could serve as a reliable technique for monitoring the outcome of vascularized bone grafting in hips with AVN. The MR imaging features indicating normal incorporation of the graft include enhancement surrounding the graft, enhancement of the

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**Figure 12** Same patient as in Fig. 3. The plain X-rays show the large osteonecrotic lesions (black arrows) and the subchondral fracture with the “crescent” sign on the left (open arrow). On the right hip joint, there is also a “tilt” deformity of the lateral femoral head (white arrow), which might contribute to hip pain by means of femoroacetabular impingement.

**Figure 13** A 43-year-old male patient with known bilateral avascular necrosis of the femoral heads and constant pain on the left hip for the last 6 months. (A) Coronal T1-weighted magnetic resonance (MR) image shows the bilateral “band-like” sign, suggesting bilateral avascular necrosis (arrows). (B) Axial and (C) coronal T2-weighted MR images show joint fluid entering a defect on the lateral aspect of the femoral neck (open arrows). This represents enlargement of a previously known herniation pit. (D) Coronal fat-suppressed T2-weighted MR image confirms the presence of fluid within the defect (open arrow) and in addition shows reactive bone marrow edema (thin open arrow) extending to the intertrochanteric area.
previously necrotic area indicating revascularization, reduction of BME, and associated reduction in the size and increase in the signal of the necrotic bone (Fig. 17). Failure of the bone grafting is characterized by presence of a low SI osteonecrotic area within the bone graft and increased surrounding bone marrow edema secondary to articular collapse (Fig. 11).

Dynamic contrast-enhanced MR has been used for the evaluation of the blood perfusion in both the diseased femoral head and transferred bone. Conventional enhanced MR occasionally depicts increased intensity in bone marrow without blood perfusion due to leakage of contrast from the capillaries into the necrotic tissue. On the contrary, using dynamic MR imaging, only images taken before leakage are evaluated, reflecting the actual blood flow in the bone marrow. A fast rise in the time intensity curves indicates fast blood perfusion. It has been found that there is little perfusion 1 month after the operation and that vascular ingrowth from the bone graft occurs between 1 and 7 months after surgery.

Figure 14 A 45-year-old male patient with a history of chronic renal failure and previous transplant. The patient received corticosteroid treatment and presents with bilateral anterior hip pain. (A, B) The coronal short tau inversion recovery magnetic resonance (MR) images show the transplanted kidney in the right iliac fossa (thin arrows). Anteriorly, there are two oval-shaped areas with fluid (short arrows). (C) The axial T2-weighted MR image confirms the presence of effusions within the iliopsoas bursae bilaterally (arrows). The marrow of the femoral heads is intact without any evidence of avascular necrosis.

Figure 15 The calculation of the index of necrotic extent using magnetic resonance (MRI) (according to Koo and Kim). (A) The angle of necrotic area in the mid-coronal image. (B) The angle of necrotic area in the mid-sagittal image. The index for necrotic extent = \( \frac{A}{180} \times \frac{B}{180} \times 100 \). On the (A) coronal T1-weighted and (B, C) sagittal fat-suppressed proton-density weighted MR images, the measurement of the extension of the lesions by creating the relative angles is shown.
SCREENING FOR AVASCULAR NECROSIS

There are limited data concerning the routine use of MR imaging in screening asymptomatic patients at risk (Fig. 18). It has been shown that a rapid (<1 minute) MR protocol can detect and quantify AVN in 92% of cases with similar reliability to that of the routine SE and TSE sequences, allowing the introduction of MR imaging earlier in the care of patients with clinical suspicion of AVN.31,68

The development of multichannel whole-body MR imaging has enabled bone marrow screening at high diagnostic accuracy.69 High sensitivity results from advances in software and hardware, such as parallel imaging techniques, moving table facilities, and high-field whole-body scanners, which have reduced acquisition times without compromising spatial resolution.69 The scarce data on the use of whole-body MR for multifocal AVN screening show that it is a promising method for early detection of asymptomatic foci.70,71

Screening for AVN might draw further attention because there is evidence that this disease is rather a multisystemic disorder not necessarily located exclusively in the skeleton. One study showed that cerebral white matter lesions are detected with high frequency (56.9%) in patients with nontraumatic AVN of the femoral head compared with age- and sex-matched controls (Fig. 19). Interestingly, in patients with corticosteroid treatment there was statistically lower prevalence (58.6%) compared with those without it (90.1%).72 The same authors showed that individuals with paraoxonase 1 192QQ genotype may have an increased risk for AVN of the femoral head and cerebral white matter lesions.73

MINIMAL AVASCULAR NECROSIS

Minimal AVN was first described in 1998 by Saito et al14 as a small and eccentrically located focal lesion

Figure 16 Quantification of the osteonecrotic lesions (according to Bassounas et al61). (A) On the coronal T2-weighted magnetic resonance (MR) image, the lesion (arrow) is well contained within the acetabulum (class IIA). (B) Coronal T1-weighted MR image in a 45-year-old male patient shows a noncontained lesion (class IIB), extending slightly outside the lip of the acetabulum, located in a non-collapsed right femoral head. The left hip shows a noncontained class IIIb lesion with a focal flattening superiorly.

Figure 17 Normal magnetic resonance (MR) imaging of the vascularized fibular graft incorporation. The fat-suppressed contrast-enhanced T1-weighted MR images in the (A) 2-week and (B) 6-week postoperative period show the fibular graft (open arrows) and the necrotic area (white arrows) that shows enhancement in (B), suggesting revascularization. The enhancement surrounding the graft (small arrow in B) is a sign of normal incorporation.
Figure 18  A young adult male patient with a history of leukemia, corticosteroid administration, and a pain of recent onset radiating to the right hip area. (A) Sagittal T1-weighted magnetic resonance (MR) image of the knee shows multiple medullary infarcts (arrows). (B) Fat-suppressed coronal short tau inversion recovery MR image shows multiple medullary infarcts in the acetabuli and proximal femora (arrows). (C) Axial fat-suppressed T2-weighted MR image confirms the presence of the femoral infarcts (arrows) and in addition shows a high signal intensity area in the right femoral quadratus muscle (open arrow). A computed tomography–guided biopsy was performed and the specimen showed muscular infarction.

Figure 19  A 28-year-old male patient with known bilateral idiopathic hip avascular necrosis. (A) Coronal T1-weighted and (B) contrast-enhanced fat-suppressed T1-weighted magnetic resonance (MR) images show the osteonecrotic lesions (arrows). Joint effusion and synovitis is also demonstrated on (B), mainly on the right hip joint. (C–E) The coronal fluid-attenuated inversion recovery MR images of the brain demonstrate multiple high signal intensity lesions in the supratentorial subcortical white matter (arrows).
at the femoral head that is believed to represent an atypical form of AVN. It is believed to be a result of a single episode of infarction rather than recurrent ischemic attacks, and its location relates to the general distribution and anastomoses of the arteries supplying the femoral head.\textsuperscript{14,15} The minimal AVN lesions are localized eccentrically in relation to the weightbearing area and extend to a limited portion of the femoral head. Due to the small size and eccentric location, minimal AVN does not lead to articular collapse. The MR imaging patterns of minimal AVN vary depending on the stage of the disease and, in general, are quite similar to the regular AVN. Recognition of the imaging characteristics of this particular form of minimal AVN can prevent misdiagnosis from other disorders of the femoral head with similar imaging appearances, such as bone tumors, insufficiency fractures, or synovial herniation pits (Figs. 20 and 21).

**LEGG-CALVE-PERTHES DISEASE**

LCP disease is a form of idiopathic AVN occurring in preadolescent children, mainly boys (peak age: 5 to 6 years) with no predisposing factors for AVN. It carries an incidence of ~0.005 to 0.016%.\textsuperscript{74} Most cases are unilateral; when bilateral (15%), the lesions are usually asynchronous.\textsuperscript{74}

MR imaging is a useful tool, complementary to plain radiographs, for the evaluation of LCP disease, allowing prompt diagnosis, accurate staging, detection of complications, and assessment of prognosis.\textsuperscript{16} MR imaging is more accurate than scintigraphy in depicting the exact extent of disease.\textsuperscript{16} The MR protocol for evaluation of a possible LCP should include both conventional and cartilage-specific sequences.\textsuperscript{16} Dynamic multiphasic imaging with digital subtraction techniques could be applied to identify subtle alterations in perfusion, increasing thus the accuracy for early depiction of LCP.\textsuperscript{75} MR arthrography of the hip may be beneficial in cases where complications affecting the labrum and cartilage are suspected.\textsuperscript{16} Additional MR techniques such as DWI may play a role in the evaluation of LCP. Preliminary data show that increased diffusivity may correlate with poor prognosis.\textsuperscript{76}

MR is both sensitive and specific for the early detection of LCP disease. During the early avascular

![Figure 20](image-url)  
**Figure 20** An asymptomatic 60-year-old male patient with a history of corticosteroid treatment because of ankylosing spondylitis. (A) Coronal T1-weighted and (B) T2-weighted as well as (C) axial T1-weighted and (D) T2-weighted magnetic resonance images show a small osteonecrotic lesion in the superomedial aspect of the femoral head (arrows).
Figure 21  A 58-year-old female patient with a pelvic hemangiopericytoma (asterisk in all images). (A) The coronal T1-weighted magnetic resonance (MR) image shows the dumbbell lesion in the right pelvis with intermediate signal intensity. The proximal femoral head bone marrow has normal signal. (B) The corresponding MR image 8 weeks following radiotherapy shows the typical “band-like” sign suggesting the presence of avascular necrosis (AVN) on the right femoral head (open arrow). A smaller lesion (minimal AVN) is demonstrated on the left side (small open arrow). (C) Seven months later, the patient became symptomatic on the right hip joint; the coronal T1-weighted MR image shows progression of the osteonecrotic lesion (open arrows). The corresponding (D) short tau inversion recovery and (E) fat-suppressed contrast-enhanced T1-weighted MR images show the bone marrow edema (white arrows) resulting from articular surface collapse (long arrow, E). The minimal AVN lesion shows moderate resolution with reduced size.

Figure 22  A 10-year-old boy with Legg-Calvé-Perthes on the right side. (A) The coronal T1-weighted magnetic resonance (MR) image shows the low signal intensity, compared with the left side, and remodeling of the femoral head epiphysis (arrow). (B) The coronal short tau inversion recovery MR image confirms the abnormality of the bone marrow in the epiphysis (open arrow) and in addition demonstrates bone marrow edema in the proximal femoral metaphysis (arrowhead). (C) The high-resolution oblique axial gradient-echo water excitation T1-weighted MR image shows the intact femoral head articular cartilage (arrows).
(necrotic) phase, which can present with normal radiographs, MR imaging reveals a variety of patterns in the proximal femoral epiphysis, including focal or diffuse low or intermediate SI on T1-weighted and high SI on STIR/fat-suppressed T2-weighted sequences. The latter can also depict a curvilinear subchondral lesion in the anterosuperior aspect of the femoral head (“crescent” sign or “Caffey” sign) representing a subchondral fracture. More advanced necrosis is demonstrated with epiphyseal low SI on all sequences, partial or complete nonenhancement 2 minutes after intravenous injection, and joint effusion and synovitis (Figs. 22 and 23). MR imaging and MR arthrography are of value for depicting possible complications of LCP disease such as premature degeneration, labral abnormalities, or intra-articular ossific fragments, and for assessing the femoral head containment and articular surface congruency.75,78

CLOSING REMARKS
Femoral head AVN is a devastating disorder affecting young patients, and despite treatment it normally follows a progressive course toward a destructive osteoarthropathy. MR imaging has gained an established role regarding accurate classification of the early stages and

Figure 23 A 9-year-old-girl with right Legg-Calvé-Perthes (LCP) disease. The plain film was unremarkable (not shown). (A) Coronal T1-weighted magnetic resonance (MR) image shows lower signal intensity of the epiphyseal bone marrow compared with the normal left (arrows). There is also a flattening of the superolateral aspect of the femoral head. (B) The coronal short tau inversion recovery MR image demonstrates right proximal femoral epiphyseal subchondral fluid signal, consistent with subchondral fracture suggesting a necrotic phase of LCP disease (arrows). There is also a right hip joint effusion.
Figure 24  An 11-year-old boy with left Legg-Calvé-Perthes disease. (A) Coronal short tau inversion recovery and (B) T1-weighted MR image show the abnormal shape (flattening of the superior femoral head) and signal of the epiphyseal bone marrow on the left (arrows). Some loss of containment is shown on both coronal images. (C) The oblique axial three-dimensional T1-weighted water excitation gradient-recalled echo MR image demonstrates the abnormality consisting of a bone bridge and disruption of the normal growth plate (arrow).

Figure 25  A 23-year-old patient with a history of leukemia and corticosteroid treatment. (A) Coronal short tau inversion recovery and (B) T1-weighted magnetic resonance (MR) images and the T2*-weighted oblique axial of the (C) right hip and (D) left hip show advanced bilateral avascular necrosis with subchondral fractures. (E) The coronal computed tomography multiplanar reconstruction confirms the subarticular sclerosis, the presence of the subchondral fractures, and the collapsed articular surfaces, in keeping with advanced disease. At this stage (ARCO IV), plain radiographs are able to classify the lesions accurately and there is no need for cross-sectional imaging.
prognosis assessment. There is definitely no role for MR imaging when the disease is advanced (Fig. 25). The evolving role of MR imaging includes investigation of multiple foci, depiction of the cause of pain, accurate discrimination between early and advanced disease, and postoperative evaluation of the vascularized grafts. In young patients with potential for joint-preserving surgery, MR arthrography may be useful for assessing the integrity of the articular surfaces of the femoral heads (Fig. 26).

REFERENCES


Figure 26 A 23-year-old male patient with known avascular necrosis of both hips. (A) Coronal T1-weighted and (B) fat-suppressed proton-density magnetic resonance (MR) images show the osteonecrotic lesions. The one on the right side is larger and associated with bone marrow edema. The high-resolution fat-suppressed T1-weighted MR arthrographic images on the (C) oblique axial planes and (D) sagittal planes show that the articular cartilage of the femoral heads is intact. This information supports a treatment decision of joint-preserving surgery.
52. Ito H, Matsuno T, Minami A. Relationship between bone marrow edema and development of symptoms in patients...
with osteonecrosis of the femoral head. AJR Am J Roentgenol 2006;186(6):1761–1770


