Magnetic Resonance Imaging of Bone Marrow: A Review – Part II

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In part I, the normal appearance, maturation pattern, benign reconversion and depletion states of bone marrow were reviewed, followed by a discussion of a collection of marrow conditions not easily categorized. In part II, we review bone marrow edema, myeloproliferative disease, marrow infiltration and replacement, and bone marrow ischemia with emphasis on their associated MR imaging characteristics. While MRI is exquisitely sensitive in the detection of marrow abnormalities, the imaging characteristics of bone marrow disease often are nonspecific with only subtle differences in distribution, signal intensity and enhancement. When findings are equivocal, attention to the location and pattern of bone marrow signal abnormality, along with the clinical history, can serve to differentiate several etiologies that secondarily affect bone marrow.

Anatomy

Within the medullary component of bone, there are trabeculae of cancellous bone providing structural support and mineral supply.[1,2] Vascular supply arises from the nutrient artery, branching into an extensive sinusoidal system traversing the marrow, and ultimately draining into the central venous system, which also exits via the nutrient foramen.[3] Nerve supply includes extensive sensory and sympathetic branches.[4] The cellular elements of normal marrow include a dominant component of fat cells, in addition to erythrocyte and leukocyte precursor cells, and reticulum or stromal cells.[5,6]

MR Imaging

T1 relaxation (spin-lattice relaxation) describes the rate at which protons, excited by the radiofrequency pulse into the transverse plane, release the absorbed energy into the surrounding tissues and regain longitudinal magnetization.[7] One of the most important factors determining T1 relaxation times in normal tissues at clinically relevant field strengths is the tissue type.[8] For example, the molecular structure of lipid contains many CH_2 groups, which demonstrate efficient spin-lattice relaxation, resulting in high signal intensity on T1-weighted images.[1] The presence or absence of marrow fat in the imaging pixel contributes significantly to its relative signal intensity. Disorders in which normal marrow is replaced by tumor (marrow replacement) would be expected to demonstrate lower T1 signal intensity than conditions in which a prominent component of marrow fat remains (marrow infiltration).[9,10] T1 relaxation time is also affected by the relative ratio of bound to unbound water in the tissues.[1,8] Consequently, a relative increase in interstitial water protons in the marrow would be expected to result in longer T1 relaxation times, as observed in the setting of marrow edema, fibrosis, or hemorrhage.[1]

T2 relaxation time is affected by the mobility of the water protons.[11] Longer T2 relaxation times may result from increased water content in the tissues, a relative increase in extracellular fluid, or more random tissue ultrastructure (e.g. trabeculae disrupted by fracture).[11-14]

In the majority of cases, spin echo sequences with T1 weighting and T2 weighting are sufficient to evaluate the marrow. Fat suppression is commonly used with the T2 weighted images to enhance conspicuity of the marrow signal abnormality. Short inversion time inversion recovery (STIR) sequences can be used in place of fat suppressed T2 weighted imaging. STIR has the advantage of more homogeneous fat suppression, but suffers from relatively decreased signal to noise ratio compared to T2 weighted images. Intravenous contrast is typically reserved for complicated cases, or cases in which infection is suspected. Some authors advocate the use of chemical shift imaging, in which similar contributions of fat and nonfat elements in the pixels causes signal decrease on out of phase

images.[15] Alternative MR imaging techniques include diffusion weighting for differentiation of pathologic from benign vertebral compression fracture, MR spectroscopy for evaluation and characterization of tumors, magnetization transfer imaging with chemical exchange saturation transfer agents, or alternative contrast agents such as superparamagnetic nanoparticles.[16-19]

Bone Marrow Edema

In the setting of injury, arthrosis, adjacent tendinosis, nearby neoplasia, reflex sympathetic dystrophy, and a variety of other causes, the bone marrow demonstrates relatively hyperintense T2 and hypointense T1 signal.[20] This is commonly referred to as a bone marrow edema pattern, although the mechanism and histological composition of bone marrow "edema" may vary depending upon the inciting disease or process.[1,21] It is postulated that there is an increase in interstitial water content, and that hyperperfusion contributes to its formation.[1,21]

A bone marrow edema pattern will typically show poorly defined margins, and faint marrow signal abnormality relative to adjacent muscle on T1 weighted images. The signal intensity of the marrow abnormality alone is generally not specific for a disease process. However, the location and distribution of marrow abnormality can often provide a clue to both etiology and, if related to trauma, the mechanism of injury. For example, when a marrow edema pattern is present at the sulcus terminalis of the lateral femoral condyle and at the posterior margin of the lateral tibial plateau, the pattern can be recognized as resulting from a pivot-shift mechanism (Fig. 1). The radiologist may then look for the associated soft tissue injuries, including anterior cruciate ligament tear, and often medial collateral ligament tear.

Another example of a characteristic bone marrow edema pattern in the knee is the posterolateral corner injury (Fig. 2). It is characterized by hyperextension with a varus directed force leading to contusion and/or fracture of the anteromedial tibia and femoral condyle, as well as injury to the lateral collateral ligament, popliteus tendon, and arcuate ligament complex. Associated avulsion of the proximal fibula may be present. This injury is commonly associated with anterior cruciate ligament tear, and may involve stretch injury of the common peroneal nerve. It is critically important to recognize this specific injury pattern because of inherent instability which requires timely surgical intervention.[22]

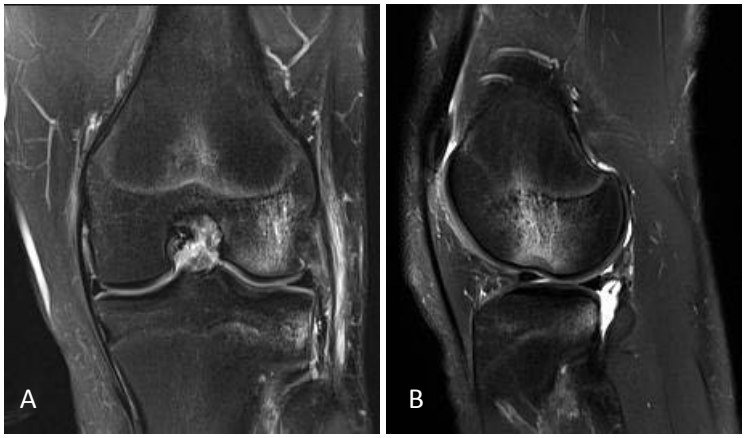

Figure 1. Coronal (A) and sagittal (B) fat suppressed T2 MR images of the left knee in a 15-year-old male with a pivot shift injury show a marrow contusion pattern of the lateral femoral condyle and tibial plateau.

Lastly, when the radiologist identifies bone marrow edema pattern involving the medial border of the patella and the lateral border of the lateral femoral condyle, a patellar dislocation-relocation injury has occurred (Fig. 3). Additional patterns of marrow edema within the knee, and corresponding mechanisms of injury are detailed in Table 1.

Abnormal marrow signal intensity isolated to the subchondral bone can be seen in a number of conditions, including underlying joint disease such as degenerative arthritis or rheumatoid arthritis, osteochondral lesion, contusion, insufficiency fracture, avascular necrosis, infection and neoplasm. In osteoarthritis, signal abnormality within the subchondral bone may result from a combination of subchondral cyst formation, fibrosis, hyperemia, necrosis, and bone marrow edema.[23] With insufficiency fracture of the knee, a condition previously called spontaneous osteonecrosis of the knee (SONK), there is signal abnormality in the region of the insufficiency fracture (Fig. 4). While somewhat controversial, a pattern of bone marrow edema involving the hip can be seen. Previously thought to represent unique entities, such diagnoses as "transient osteoporosis," "regional

migratory osteoporosis", and "bone marrow edema syndrome" are now thought to represent a spectrum of disease related to underlying insufficiency or stress fracture (Fig. 5).[24] Additional diseases that may affect the subchondral marrow are listed in Table 2.

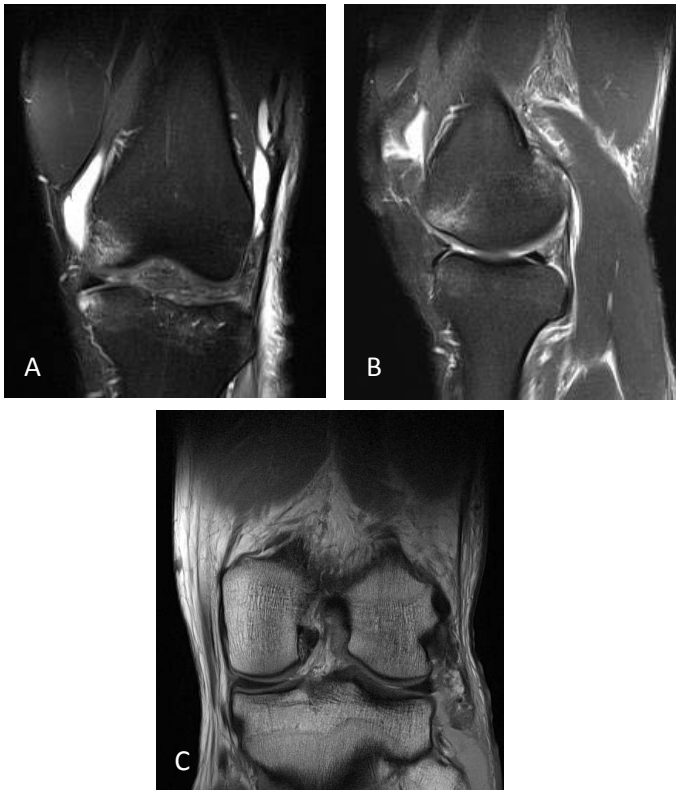

Figure 2.Coronal (A) and sagittal (B) fat suppressed T2 images of the left knee in a 28-year-old male show bone marrow contusion of the anteromedial aspect of medial femoral condyle and tibial plateau. Coronal proton density weighted image of the left knee (C) shows disruption of the lateral collateral ligament.

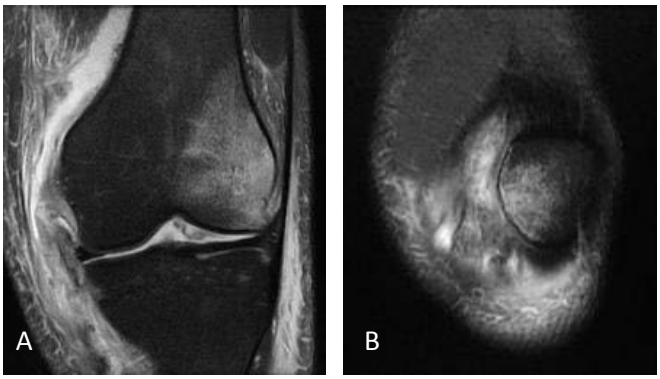

Figure 3. Coronal T2 images of the left knee in a 20-year-old female with marrow contusions involving the lateral femoral condyle (A) and medial patella (B), consistent with lateral patellar dislocation and relocation injury.

Table 1 – Complex Knee injuries and bone marrow contusions
Ten mechanism-based injury patterns (22)

Bone Contusion or Fracture Locations	Mechanism of injury
Anterior femur and tibia	Pure hyperextension (kicking)
Anteromedial tibia and femur, posterolateral corner, proximal fibula avulsion	Hyperextension with varus (posterolateral corner injury)
Anterolateral tibia and femur, posteromedial tibial avulsion	Hyperextension with valgus
Lateral tibia and femur	Pure valgus
Medial tibia and femur	Pure varus
Lateral femur and posterolateral tibia, posteromedial tibia and femur avulsion or contrecoup lesion	Flexion with valgus and external rotation
Lateral femur, posterolateral tibia, posterolateral tibia and fibular head avulsions	Flexion with varus and internal rotation
Medial patella, lateral condyle	Patellar dislocation
Directly at trauma site	Direct trauma
None, unless severe force or axial load	Flexion with posterior tibial translation

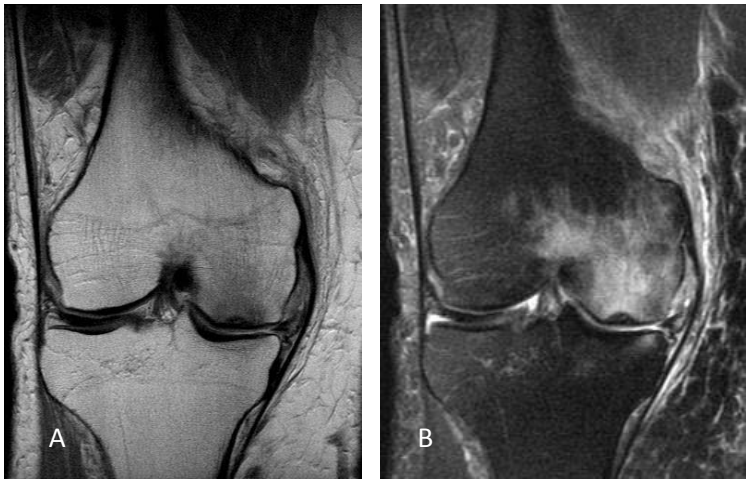

Figure 4. Coronal proton density (A) and fat suppressed T2 (B) weighted images of the right knee in a 77-year-old male show insufficiency fracture involving the mesial medial femoral condyle.

Table 2 - Joint diseases which secondarily affect adjacent subchondral bone (23)

Septic arthritis	Amyloid arthropathy
Rheumatoid arthritis	Hemophilic arthropathy
Ankylosing spondylitis	Pigmented villonodular synovitis
Gout	Neuropathic arthropathy
Milwaukee shoulder	Foreign body synovitis
Rapidly destructive articular disease	Primary synovial osteochondromatosis

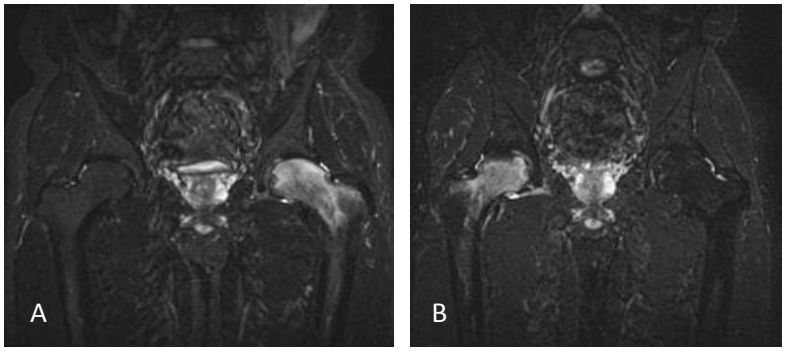

Figure 5. Coronal STIR image (A) demonstrates hyperintense signal throughout the left femoral head, neck and intertrochanteric region. Coronal STIR image acquired at a later date (B) demonstrates complete resolution of signal abnormality in the left proximal femur with new hyperintensity in the right femoral head and neck with some extension into the proximal diaphysis.

A subtendinous, subligamentous and subphyseal location of marrow signal abnormality can also be useful in identifying potential etiologies. Subtendinous bone marrow edema is commonly associated with trauma (acute or chronic) such as tendon tear. However, tenosynovitis, hydroxyapatite deposition disease (HADD), and enthesitis are also common causes of subtendinous bone marrow edema. With HADD, deposition of hydroxyapatite crystal may occur within the tendon, bursa, or joint capsule, causing focal inflammation.[25] This can be idiopathic or due to underlying systemic abnormality such as secondary hyperparathyroidism or renal osteodystrophy. Subligamentous bone marrow edema may be associated with disease of adjacent tendons or ligaments.[26,27] Renal osteodystrophy has a predilection for bone resorption in both subligamentous and subphyseal locations. Lastly, subphyseal bone marrow edema can also be seen with focal physeal injury and rickets (Fig. 6).[28]

Proliferative Disorders

Myeloproliferative disorders involve both benign and malignant diseases arising from proliferation of cells normally found in bone marrow. Marrow reconversion is considered a physiologic response to stress and was discussed in part I of our review. The subset of benign myeloproliferative diseases includes myelofibrosis, polycythemia vera, mastocytosis and myelodysplastic syndrome. The subset of malignant proliferative disorders includes leukemia and monoclonal. Monoclonal gammopathies are further subcategorized as either as aggressive (multiple myeloma, primary amyloidosis, Waldenstrom macroglobulinema and lymphoproliferative disorder) or nonmyelomatous (monoclonal gammopathy of undetermined significance and borderline significance).[29]

Multiple myeloma

Multiple myeloma (Fig. 7), amyloidosis and Waldenstrom macroglobulinemia are aggressive gammopathies with very similar MR features. While a useful discriminator in Waldenstrom macroglobulinemia is the presence of regional bone infarction, the appearance of these entities on MRI is quite variable. Marrow patterns may be normal, focal disease with hypointense T1 signal marrow lesions, marrow with diffuse heterogeneous or variegated signal, or marrow with diffuse homogeneous hypointense T1 signal. To complicate things further, any combination of these patterns can be found in patients with disease regression or progression.[29]

Focal myelomatous lesions are often characterized by hypointense T1 signal intensity unless there is hemorrhage causing focal T1 hyperintensity. The T2 signal intensity of these lesions is highly variable. Unfortunately, the appearance of myeloma on MRI can be indistinguishable from metastatic disease. Occasionally, focal myeloma lesions can demonstrate a 'mini-brain' appearance on MRI with thick osseous struts radiating in from the outer margins of the lesion (resembling the sulci and gyri pattern of the brain), a feature which can help differentiate it from metastatic disease.[30] Although MRI may be less helpful in determining a specific diagnosis, MRI proves most useful in the preprocedure planning for bone marrow biopsy, as well as evaluating disease progression and treatment response.[29,31]

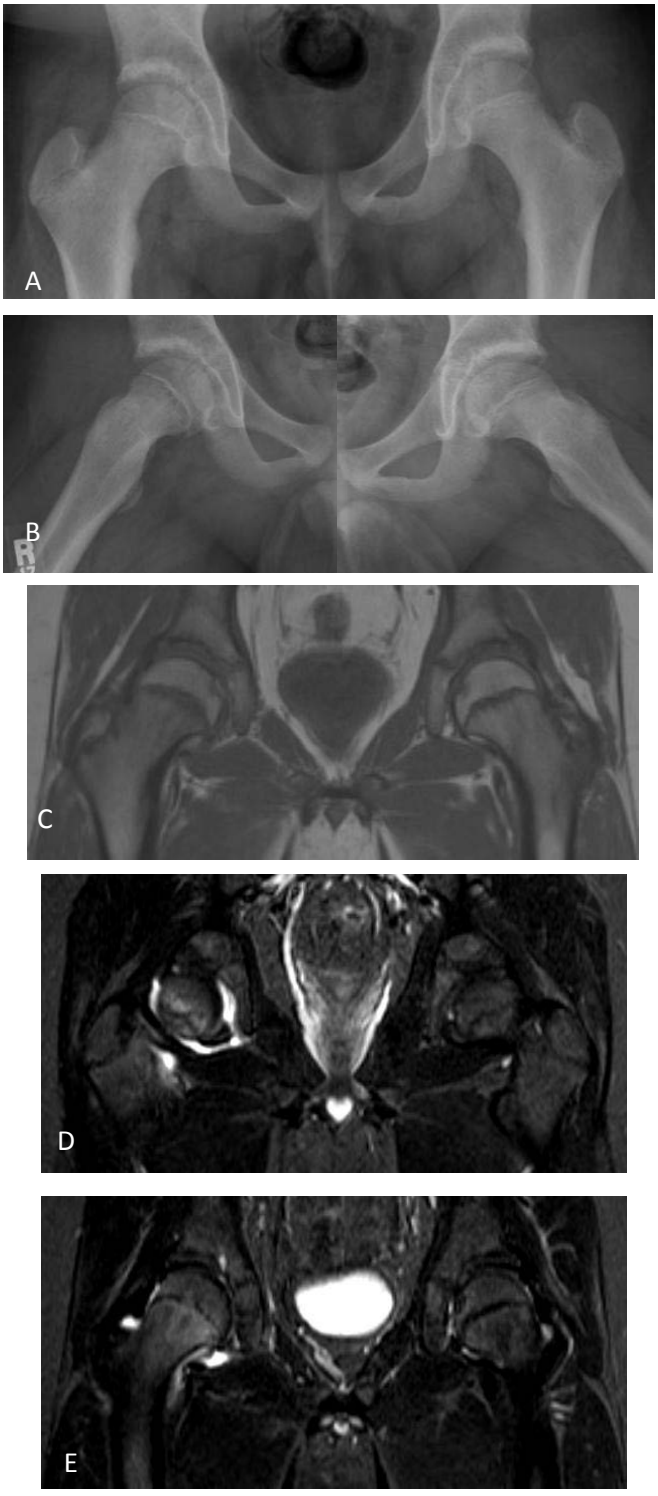

Figure 6. AP (A) and frog-leg lateral (B) views of the hips demonstrate a slipped physis on the right. Coronal T1 image (C) reveals widening of the affected right growth plate, as well as hypointense signal along the physis, most notable inferiorly. Coronal T2 weighted images (D and E) demonstrate hyperintense signal on either side of the physis, as well as a right-sided joint effusion.

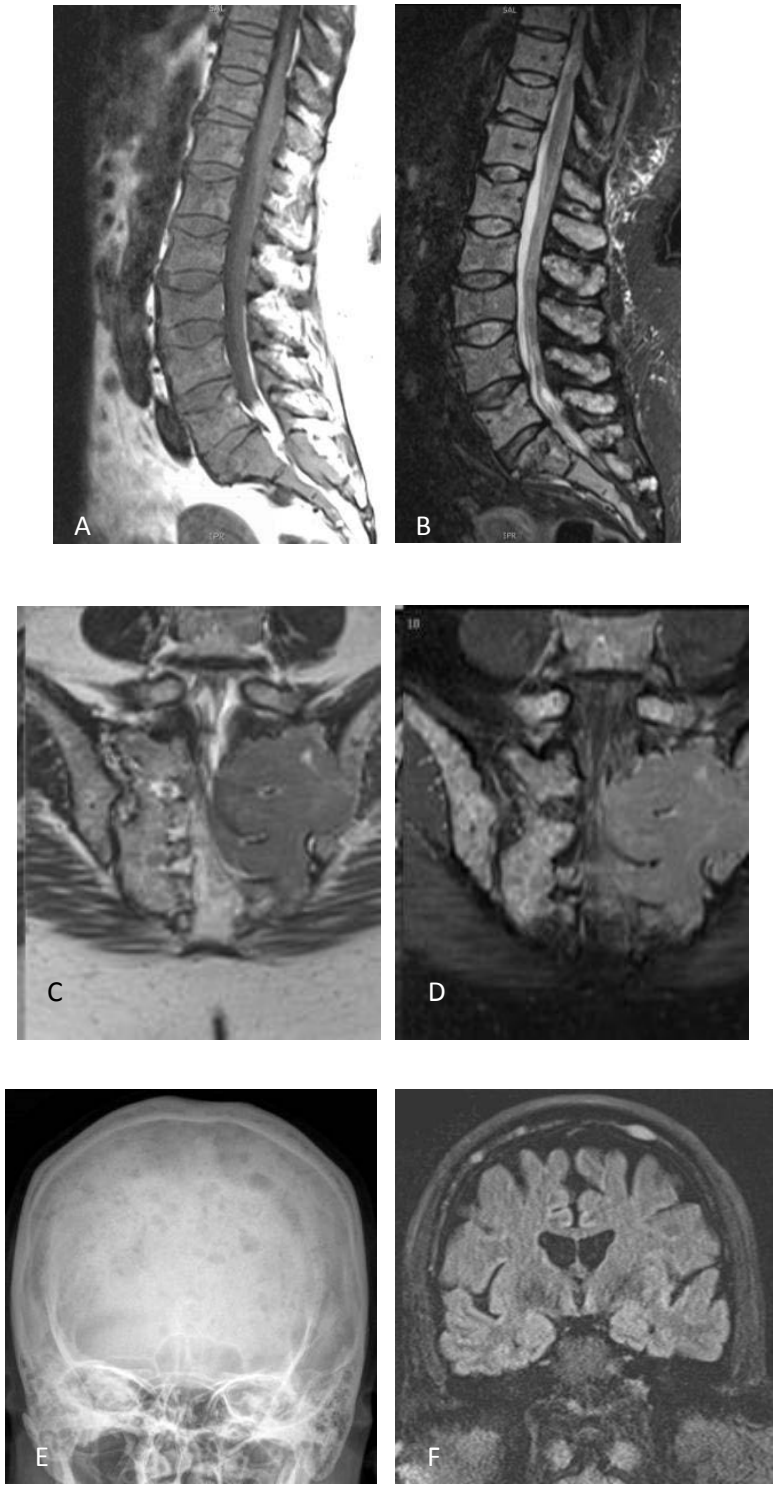

Figure 7. Sagittal T1 (A) and T2 (B) MR images demonstrate heterogeneous bone marrow signal with subtle endplate deformities. Coronal T1 pre (C) and post (D) contrast images of the sacrum reveal an enhancing left sacral mass. Frontal skull radiograph (E) demonstrates numerous lytic calvarial lesions. Coronal FLAIR image of the brain (F) shows increased signal intensity associated with the calvarial lesions.

Leukemia

Leukemia is a disease characterized by proliferation of leukemic cells that replace normal marrow constituents. Both acute and chronic forms of leukemia commonly demonstrate diffuse marrow abnormality. Abnormal signal that extends into the epiphyses and apophyses may also represent red marrow hyperplasia due to replacement of red marrow by leukemia in the axial skeleton. On T1 weighted images, leukemic infiltrate has hypointense signal intensity (lower than disc or muscle). The T2 weighted signal is variable relating to the infiltrative nature of leukemic cells. More often than not, there is hyperintense signal relative to fat on T2 weighted and hyperintense signal relative to muscle on STIR images.[29] Homogenous hypointense T1 signal may be difficult to appreciate in the setting of extensive bone marrow disease when no normal marrow is available for comparison. In this case, contrast enhanced imaging can help to show enhancement of abnormal bone marrow compared to adjacent discs. After the diagnosis has been made, MRI can be used to monitor for complications of leukemia such as osteomyelitis, hematoma and chloromas (solid tumors of granulocyte precursor cells occasional seen in acute leukemia).[31] Serial MRI can also be used to monitor the status of disease remission and relapse.[29]

Mastocytosis

Mastocytosis is a rare disorder of mast cell proliferation. It generally presents as a self-limited dermatologic disorder, urticaria pigmentosa. Rarely, a systemic form may present with involvement of internal organs and bone marrow. Osseous involvement usually affects the axial skeleton. On radiographs, nonspecific areas of lytic, sclerotic, or mixed lytic-sclerotic abnormality are seen in either a focal or diffuse distribution. MR imaging findings are generally nonspecific, ranging from normal to focal or diffuse heterogeneous signal within the bone marrow.[32]

Marrow Infiltration and Replacement

Bone marrow may contain cellular areas (red marrow), or may be infiltrated by edema and inflammatory cells in the setting of osteomyelitis. At MRI, these processes may demonstrate similar signal intensity, which has been referred to as a "marrow infiltration" pattern.[9,33] In the case of marrow with hematopoietic tissue, this terminology probably does not accurately reflect the histology, which may be better described as red marrow reconversion.[1] On T1 weighted images, a marrow infiltration pattern is characterized by subtle to moderate decrease in signal intensity which remains relatively hyperintense compared to adjacent muscle or normal intervertebral disks.[9] The margins of the marrow signal abnormality are typically poorly defined, and the signal intensity is often heterogeneous.[9] The relative hyperintensity is attributed to the residual presence of marrow fat in the imaged tissue.[1,9]

Osteomyelitis

Distinguishing between red marrow and osteomyelitis is generally straightforward. Red marrow is commonly diffuse and symmetric, with faint T1 and T2 signal abnormality. On the other hand, in osteomyelitis, infiltration by inflammatory cells and an increase in local extracellular fluid cause areas of hypointense signal on T1 weighted images and hyperintense signal on T2 weighted images (Fig. 8). The signal abnormality is often focal or confined to a geographic area. In addition, osteomyelitis which has formed a phlegmonous or abscess cavity may show the 'penumbra sign' on T1 weighted images. This is characterized by a central hypointense to intermediate T1 signal cavity surrounded by a discrete peripheral rim of relatively hypointense T1 signal. This decreased T1 signal represents adjacent reactive new bone formation and/or surrounding edema.[34] Secondary findings of skin ulcer, cellulitis, abscess, sinus tract in the soft tissue or bone, foreign body, cortical destruction and periosteal reaction often improve specificity and help to delineate osteomyelitis from other entities.[32,35]

Malignancies

Bone marrow may have regions in which normal marrow constituents are replaced by pathologic tissue, such as in the setting of malignancies with bone metastases. At MRI, replacement of normal marrow fat by tumor would be expected to

demonstrate a marked decrease in T1 signal intensity, with resultant similar signal intensity as adjacent muscle or normal intervertebral disks.[1,9] Although this finding is helpful when present, its sensitivity in the setting of early disease or low tumor burden is not well established. Additionally, this finding is not adequately specific to distinguish between benign and malignant causes, or between primary and secondary disease.

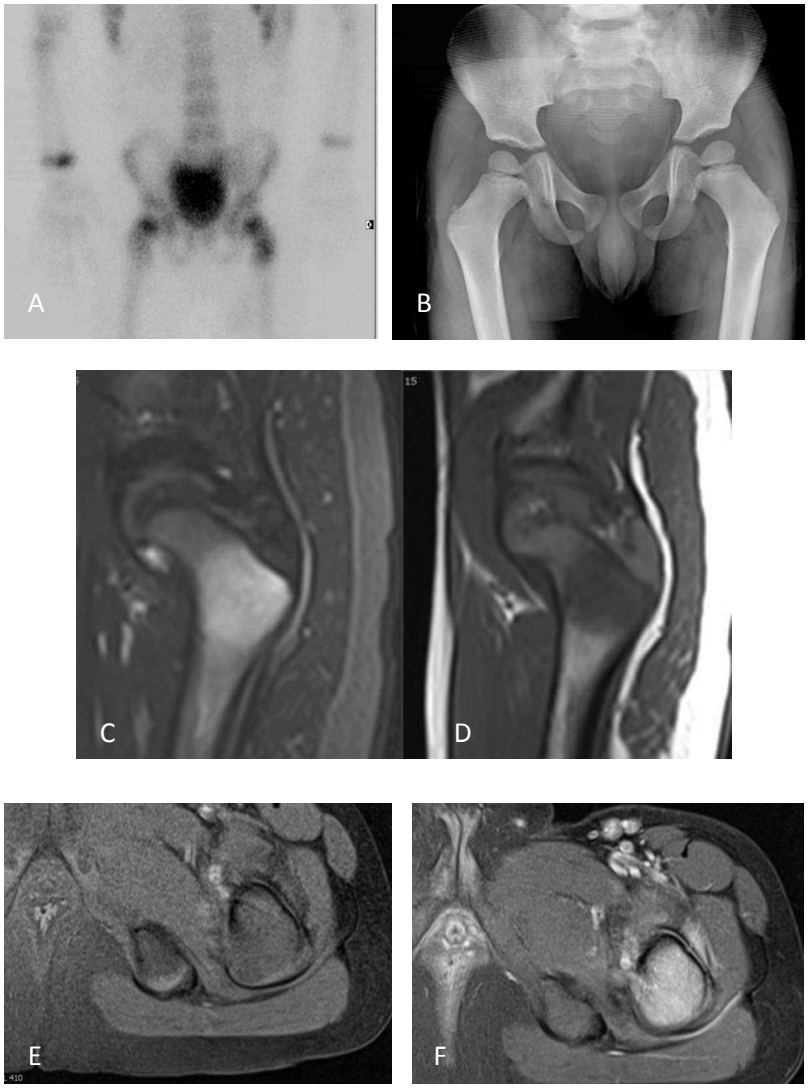

Figure 8. Nuclear medicine bone scan image (A) in a 4-year-old boy with bacteremia demonstrates mild focal radiopharmaceutical uptake in the left femoral inter-trochanteric region. No radiographic abnormality is seen (B). STIR (C) and T1 (D) weighted images angled through the left femur demonstrate hyperintense T2 and hypointense T1 signal in the region. Axial T1 pre (E) and post-contrast (F) images show enhancement of this region.

In long bone fractures, MRI features that have been found to be useful in distinguishing pathologic fractures from stress fractures include a well-defined T1 signal abnormality, endosteal scalloping, adjacent muscle signal abnormality, and a soft tissue mass.[36] When the marrow abnormality is diffuse enough such that no normal marrow is visible, it may not be obvious to the interpreting radiologist. It can be useful to observe the "flip-flop" pattern of hyperintense T2 signal intensity and hypointense T1 signal intensity in areas that typically have fatty marrow, such as the epiphyses of long bones.[37] Additionally, when the bone marrow is diffusely replaced, complications such as pathologic fracture may not demonstrate a substantial change in marrow signal intensity, making diagnosis difficult.

The most common malignancies with a predilection for bone metastasis are breast, prostate, thyroid, lung, kidney, and pancreatic carcinomas. These account for more than 80% of primary tumors presenting with bony metastases.[38] In general, metastases more commonly involve the axial skeleton (spine, pelvis, ribs and sternum), but disease may also involve the proximal femora and humeri. Peripheral disease involving hands and feet is less common, but when present often indicates underlying lung malignancy.[39]

Metastases typically appear as multifocal lesions with hypointense signal on T1 weighted images (lower than disc or muscle) and hyperintense signal on T2 weighted images. Additionally, diffuse marrow involvement, in either a homogeneous or heterogeneous pattern can be seen.[29] Metastatic lesions may demonstrate a 'halo sign', where tumor deposits have a peripheral rim of hyperintense T2 signal intensity.[40,41] This most commonly occurs with prostate and some forms of breast metastases which often have lower T2 signal than other types of metastases because of their osteoblastic nature (Fig. 9). The halo sign may also be seen in aggressive primary bone tumors and osteomyelitis, though clinical history and radiographic findings should help to discriminate between these entities.[41] Contrast enhanced studies may be useful to evaluate bone marrow abnormalities but are usually reserved for diffuse marrow abnormalities and cases in which noncontrast image findings are

nonspecific. Generally, metastatic disease will enhance to a greater degree than normal hematopoietic marrow except for those with marrow hyperplasia or immature marrow as seen in children.[31]

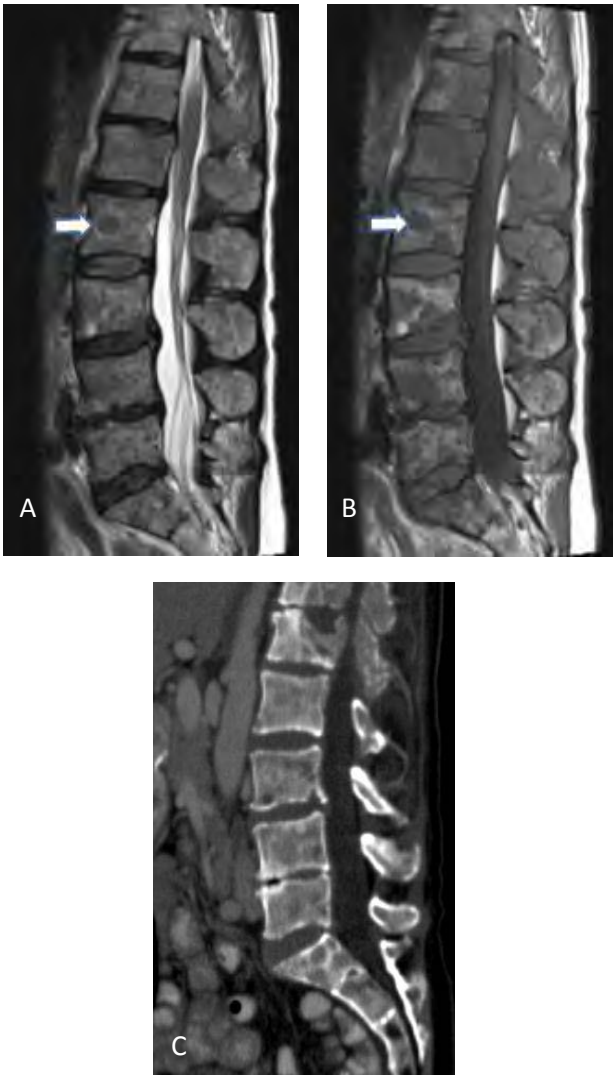

Figure 9. Sagittal T2 (A) and T1 (B) MR images in a patient with metastatic breast cancer demonstrate heterogeneous signal throughout the bone marrow with numerous hypointense lesions. A lesion within the L2 vertebral body demonstrates a halo sign with peripheral rim of increased T2 and T1 signal (arrows). There is a corresponding region of a faint rim sclerosis on CT (C). CT also demonstrates heterogeneous attenuation with foci of sclerosis throughout the spine, as well as a compression deformity at the superior L1 level.

In children, metastases and lymphoma tend to present with focal bone lesions; however, diffuse marrow infiltration can be seen with rhabdomyosarcoma and neuroblastoma.[42] MRI is useful when bone pain and laboratory values suggest malignancy but other imaging studies fail to demonstrate lesions. MRI may also be used to determine extent of disease within marrow as well as involvement of surrounding structures. It may occasionally be used to follow response to therapy.[29]

Benign versus pathologic fracture

An important use of MRI includes differentiating metastatic vertebral body fracture from osteoporotic or insufficiency fracture. Metastatic disease often shows diffuse involvement of the vertebral body with hypointense T1 signal, abnormal marrow signal extending into the pedicle and posterior elements, significant enhancement, multiplicity and adjacent enhancing soft tissue mass. On the other hand, MRI findings favoring osteoporotic compression fracture over pathologic fracture include a low signal intensity band in the vertebra, spared normal bone marrow within the vertebral body, retropulsion of a posterior bone fragment, and multiple compression fractures.[43] Insufficiency fractures may demonstrate thin paraspinal soft tissue mass or hemorrhage; however, these lesions demonstrate little to no enhancement and improvement or resolution on follow-up imaging.[32]

Sometimes, bone marrow edema from osteoporotic fracture is so extensive that no residual fat can be seen on T1 images. Some institutions use chemical shift or in and out-of-phase imaging to differentiate neoplasia from non-neoplastic entities by demonstrating coexistent fat and water in the region. Neoplasia often completely replaces the marrow fat and demonstrates no significant decrease in signal on out-of-phase images. This technique may be less useful in evaluating myeloproliferative and some infiltrative disorders that can present with a mixture of abnormal cells and normal marrow fat, leading to a false negative result.[44] False positive results may occur in cases of marrow fibrosis with complete loss of marrow fat, mimicking neoplastic infiltration.[45]

Lymphoma

Lymphomatous involvement of bone marrow on MRI is similar in appearance to metastatic disease

and is most commonly seen with non-Hodgkin lymphoma.[46] When lymphoma involves the bone marrow, it is categorized as stage IV or extensive systemic disease.[31] As with other infiltrative disorders, the extent of tumor burden correlates with MRI findings. Involved bone marrow may be normal when tumor burden is low. With more extensive disease, marrow abnormality can appear focal or diffuse with a pattern of involvement which may be patchy and heterogeneous or homogeneous. Lymphoma within marrow is characterized by hypointense T1 and T2 signal of involved portions of the bone marrow which enhance, a nonspecific pattern common to many of the infiltrative and replacement diseases. MRI may also show adjacent soft tissue mass without cortical destruction which is suggestive of but not diagnostic of lymphomatous involvement. Generally speaking, MRI is not typically used to definitively diagnose, stage or follow lymphoma but can be used to help direct bone marrow biopsy to aid in staging.[31,46]

Primary benign bone tumors

Numerous primary benign bone tumors can be considered in the differential diagnosis of focal marrow replacement. Enchondroma is a benign chondroid lesion found in the marrow cavity originating from continued growth of displaced, benign cartilaginous rests from the growth plate. Enchondroma is usually lobular in appearance with nonmineralized portions of enchondroma demonstrating low to intermediate T1 signal and intermediate to high T2 signal. The mineralized and septated portions usually show hypointense signal in both T1 and T2 weighted sequences. Additionally, they may show peripheral or septal enhancement (Fig. 10). Occasionally enchondroma may demonstrate speckled areas of hyperintense T1 signal secondary to residual areas of fatty marrow; however, the MRI signal intensity and enhancement pattern are nonspecific and it may be difficult to separate enchondroma from a low-grade chondrosarcoma. Differentiating this benign process from chondrosarcoma is more often based on a few clinical and imaging findings: the size of the lesion, pain, the amount of endosteal scalloping (depth and extent of lesion), cortical destruction, bony remodeling and/or thickening, soft tissue mass, periosteal reaction and pathologic fracture.[47]

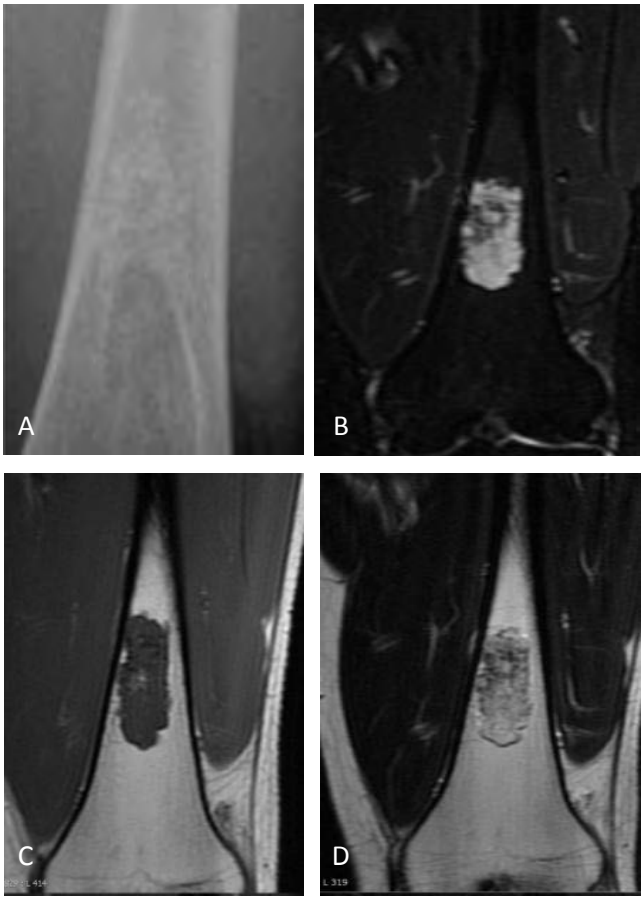

Figure 10. Enchondroma in an adolescent female. Coned-down AP radiograph of the distal femur (A) demonstrates a circumscribed lytic lesion with a narrow zone of transition and subtle calcifications in an "arcs and swirls" pattern along its superior margin. Coronal STIR image (B) reveals the lesion to be predominantly hyperintense with foci of hypointensity corresponding to calcifications. Coronal T1 pre (C) and post-contrast (D) images demonstrate a narrow zone of transition with enhancement throughout the lesion.

Primary malignant bone tumors

Primary malignant bone tumors that may involve bone marrow include osteosarcoma, Ewing and primary bone lymphoma. Osteosarcoma is the most common primary bone tumor in young adults. MRI is vital in the preoperative staging of osteosarcoma as it determines the extent of disease in the bone marrow, including skip lesions within an affected bone, adjacent soft tissue, joint or neurovascular involvement, and regions of viable tumor and matrix which can improve biopsy accuracy. Like the majority of replacement diseases, osteosarcoma

demonstrates nonspecific hypointense to intermediate signal on T1 weighted images and hyperintense signal on T2 weighted images. Regions of hypointense signal on both T1 and T2 weighted images are secondary to mineralized osseous matrix. Additional variability in appearance may be secondary to central hemorrhage or necrosis.[48]

Sarcoidosis and LCH

Non neoplastic systemic diseases may also affect bone marrow, most notably sarcoidosis and Langerhans cell histiocytosis. Sarcoidosis is an inflammatory disorder characterized by noncaseating granulomas that can be found anywhere throughout the body. Radiographs may be normal or demonstrate lacelike osteolysis and rarely osteosclerotic lesions. It usually involves the small bones and only rarely affects long bones or the axial skeleton. MRI findings may be variable with focal ill-defined or well circumscribed lesions, as well as patchy and confluent infiltration (Fig. 11).[49] Langerhans cell histiocytosis (LCH) is a spectrum of disease with idiopathic proliferation of histiocytes and granulation formation that can have focal or systemic manifestations. Focal and diffuse forms most commonly present with osseous lesions. Disseminated disease may demonstrate generalized osteopenia. As with other marrow replacement disease, LCH demonstrates nonspecific signal abnormality, hypointense signal on T1 and hyperintense signal on T2-weighted images. Even though historically LCH has been diagnosed and followed with conventional radiography or scintigraphy, MRI may helpful in demonstrating bone marrow abnormality earlier in the disease process.[50]

Marrow Ischemia

Bone marrow ischemia can occur from microvascular occlusion or from increased intraosseous pressure. Other causes of osteonecrosis include chemotherapy, steroids, or recurrent malignancy which can involve marrow focally or diffusely. When bone marrow becomes ischemic, the hematopoietic cells are affected first, undergoing cell death often within the first 6-12 hours.[51] The osteoclasts, osteocytes, and osteoblasts may survive up to 48 hours after the insult, and the fat cells may survive for 2-5 days.[1,50] Subsequent to the insult and cell death, the tissue undergoes an inflammatory and reparative response characterized histologically by inflammatory cells, increased vascularity, fibroblastic tissue, and granulation tissue.[1,51]

MR imaging findings reflect these histologic alterations. Increased T2 signal intensity and decreased T1 signal intensity are present in acutely ischemic areas with associated edema (Figs. 12 and 13). A “double line sign” on MRI is a curvilinear region of low signal intensity on T2 weighted images in the region of necrotic bone, with an adjacent high signal intensity band which correlates with the tissue’s inflammatory and reparative response. Secondary fracture of the subchondral bone cortex demonstrates articular incongruity, a marrow edema pattern, and low signal intensity curvilinear regions correlating with trabecular fracture. MRI has been shown to be exquisitely sensitive for bone marrow ischemia, approaching 100%.[1]

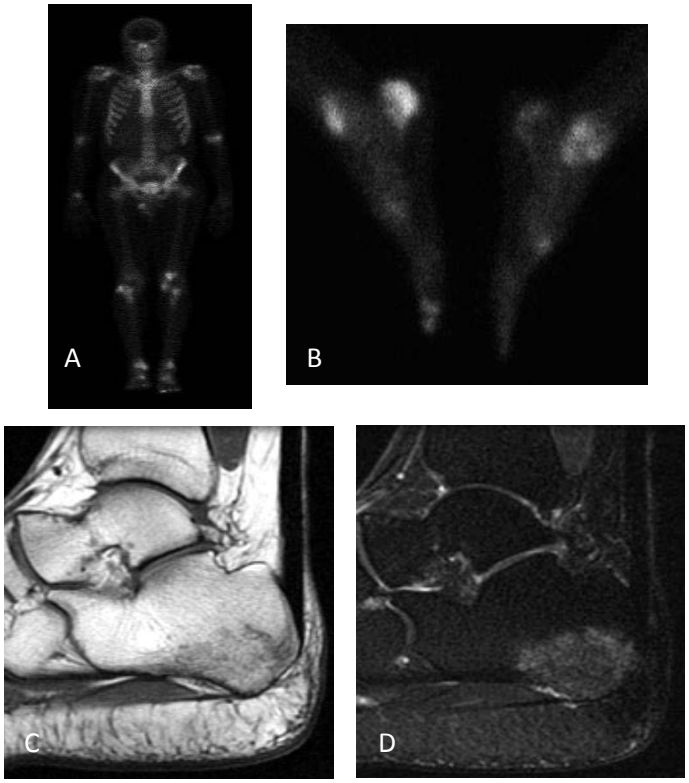

Figure 11. Patient with known sarcoid. Whole body bone scan (A) reveals multifocal regions of increased osseous uptake. Focal uptake is seen within the right posterior calcaneus (B). Coronal T1 (C) and STIR (D) images demonstrate focal decreased and increased signal intensity within the posterior calcaneus, respectively.

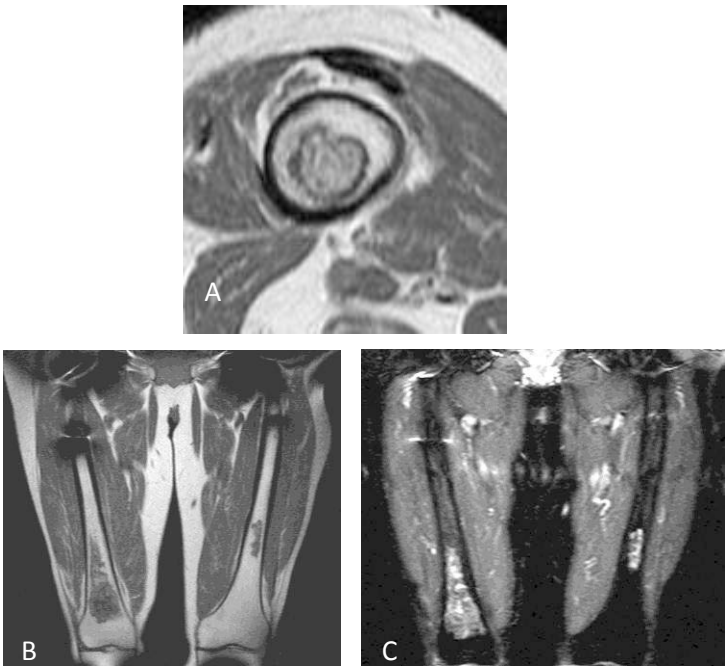

Figure 12. Bone infarcts. Axial T1 image through the femur (A) demonstrates a medullary cavity lesion with a hypointense peripheral rim and heterogeneous but slightly decreased T1 signal centrally. Coronal T1 image (B) reveals bilateral hypointense femoral lesions. Coronal STIR image (C) shows heterogeneous increased signal intensity within the lesions.

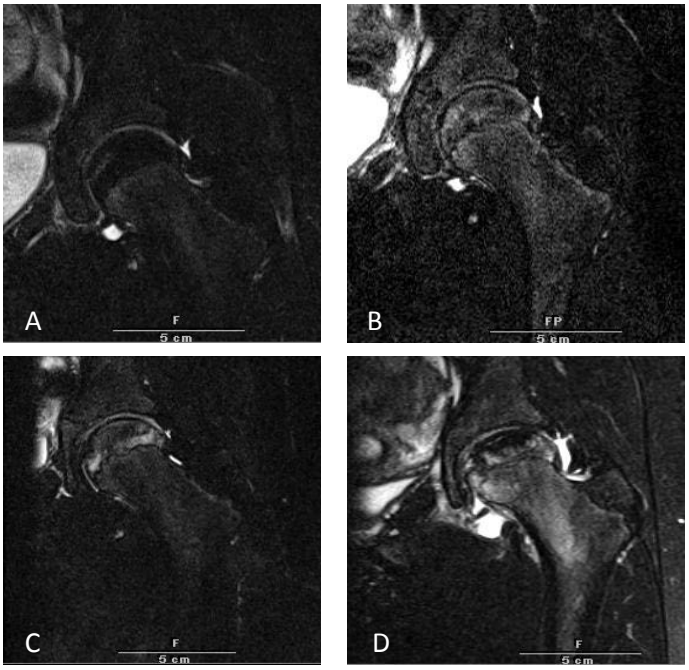

Figure 13. Avascular necrosis in development. Initial coronal STIR image (A) is normal. Follow-up images from subsequent studies reveal increased signal along the physis (B); followed by a linear subchondral hypointense line, along with increased signal along the physis (C); and finally subchondral decreased signal with collapse, along with diffuse increased signal intensity within the femur (D).

Summary

MR imaging is useful in evaluating the bone marrow, with high sensitivity in diagnosing marrow disease. The T1 relaxation times within the marrow reflect the tissue types within the imaging voxels, particularly marrow fat, and are also affected by the relative amount of extracellular fluid present in the tissue. We have reviewed the MR imaging characteristics of a number of disease processes that affect the marrow, including marrow edema, proliferative disorders, infection, marrow replacement by tumor, and ischemia. When findings are equivocal, attention to the location and pattern of bone marrow signal abnormality, along with the clinical history, can serve to differentiate several etiologies that secondarily affect bone marrow. Future research may be useful to delineate MRI findings among these diseases with greater specificity.

The views expressed in this material are those of the author, and do not reflect the official policy or position of the U.S. Government, the Department of Defense, or the Department of the Air Force.

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