Chapter 8
Musculoskeletal Imaging
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Introduction
Imaging studies are an integral part of orthopaedic practices. As the availability of imaging modalities increases, having a working knowledge and understanding of the indications of each modality is becoming increasingly important for orthopaedic surgeons. Recent advances in technology, indications for each imaging test, and imaging features of common pathologies will be discussed in this chapter.

Radiography

Advances in Technology
Since the discovery of x-rays in 1895, images have been captured and reviewed on silver halide–based hard films. Although digital image acquisition began in the mid 1980s, filmless methodology became available in the early 1990s with the advent of picture archiving and communication systems. Computed radiography, a cassette-based photostimulable phosphor and plate reading storage system, initially replaced the analog screen film system. Alternate (cassetteless) technologies for digital imaging, historically categorized as digital radiography, appeared in the mid 1990s. The digital radiography system reads the x-ray signal immediately after exposure with the detector in place.

Currently, the term digital radiography is used to refer to all types of digital radiographic systems for both cassette and cassetteless operations. The efficiency of digital radiography has markedly improved; however, without constant quality control there is a potential risk of a gradual increase in patient radiation dose (dose creep). Digital radiography systems must provide quality imaging services and protect patients from unnecessary radiation.1,2

Fracture Imaging
Spine Fractures
Although cervical spine radiography is limited in visualizing ligamentous injuries, quality radiographs can exclude unstable cervical spinal injuries in a high percentage of patients.

Cervical spine radiography is no longer used to rule out injuries to the cervical spine in high-risk multitrauma patients when CT of the head or other body parts is performed. For patients with more than a 5% risk of a cervical spine fracture, CT of the cervical spine is more efficient than obtaining multiple radiographic views.3,4 In patients with traumatic injuries, radiographic studies often require several exposures and may not detect up to 61% of cervical spine fractures.5 CT screening is also a cost-effective modality in patients at high or moderate risk for cervical spine fracture.6

Patients 65 years or older with blunt trauma have characteristic injury patterns and require special diagnostic strategies. Approximately two thirds of the fractures involve the upper cervical spine (level C0-C2) and can be caused by low-energy mechanisms such as a fall from standing7 (Figure 1). A retrospective analysis of cervical spine injuries in elderly patients (age 65 to 75 years compared with those older than 75 years) suggested that CT may be appropriate as the primary modality for all trauma patients older than 75 years because of increased incidence of injuries in low-energy mechanisms.7 For these patients, radiographic detection of cervical spine fractures is often difficult due to degenerative changes.

AP, lateral, open-mouth, and swimmer’s views are often used in imaging of the cervical spine. The lateral view should include the C7-T1 junction (Figure 2). Quality radiography remains a valuable screening test for thoracic and lumbar spinal fractures. Because the shoulders overlap on lateral views, visualization of the upper thoracic spine is often limited. CT is increasingly being used to diagnose or exclude thoracic and lumbar spine fractures, especially in patients with multiple traumatic injuries.

Fractures of the Extremities
The diagnosis and assessment of extremity fractures are the most common indications for radiography. At least two orthogonal views should be obtained because the fractures may not be seen on a single view. Additional and/or special views are commonly used for the wrist, elbow, shoulder, and ankle. The cross-table lateral view

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can be used to detect fluid-fluid levels (lipohemarthrosis) in the knee. Adjacent joints should be examined separately if there is a clinical suspicion of injury. Radiography can detect radiopaque foreign bodies; however, ultrasound has higher sensitivity for detecting foreign bodies. Radiographs are less sensitive for detecting fractures in severely osteopenic patients. Certain fractures, such as scaphoid, radial head and/or neck, and proximal femoral fractures are easily missed by radiography.

Scaphoid Fractures
The scaphoid is the most commonly fractured bone in the wrist. Early diagnosis is important because immediate treatment minimizes the risks of nonunion and osteonecrosis. Standard radiographic imaging includes PA, oblique, lateral, and scaphoid (ulnar flexion) views. Imaging protocols, including the indications for advanced techniques such as MRI, may vary from hospital to hospital.

Radial Head and/or Neck Fractures
The radial head capitellar view (oblique lateral) may be added to AP and lateral views of the elbow to detect subtle fractures of the radial head and/or neck. The fat pad sign (capsular distention), even without obvious fracture, is highly predictive of an occult intra-articular fracture (Figure 3).

Proximal Femoral Fractures
Nondisplaced fractures of the femoral neck or intertrochanteric region may be missed on standard radiographs in patients with osteopenia. Because of the serious consequences of a delayed diagnosis, limited MRI (coronal images through both hips) may be indicated for early diagnosis or to exclude the presence of a fracture.

Arthritis
The diagnosis of arthritis is primarily based on radiographic findings. Radiography is not sensitive for detecting early soft-tissue changes; however, characteristic bony changes often lead to a specific diagnosis. Classic radiographic assessment for arthritis includes evaluation of joint alignment, bone mineral status (osteopenia), cartilage (joint space, erosion), and distribution of the affected joints. A weight-bearing study is necessary to assess joint-space narrowing in the hip, knee, and ankle joints.

Rheumatoid Arthritis
Proximal joints of the hand and foot are typically affected by rheumatoid arthritis. Periarticular soft-tissue swelling, osteopenia, marginal erosion, and uniform joint-space narrowing are characteristic radiographic findings. A semisupinated oblique view of the hand and wrist (so-called ball-catcher view) will better show metacarpophalangeal and pisotriquetral joint erosions.

Osteoarthritis
Osteoarthritis (OA) affects the cartilage in weight-bearing joints of the hip and knee and is characterized by increased bone mineralization (subchondral sclerosis), osteophyte formation, and nonuniform joint-space narrowing. Identical radiographic findings in the distal joints of the hand and foot, which typically occur in women 50 years or older, are referred to as idiopathic OA. Radiographic findings of OA in the hands may be associated with central erosive changes and typically occur along the articular surfaces. This variant is called erosive OA. The erosive changes may be accompanied by osteopenia or proliferative changes.

Pyrophosphate Arthropathy
Calcium pyrophosphate dihydrate crystal deposition occurs in the soft tissues in and around a joint and may cause synovitis. Pyrophosphate arthropathy typically affects elderly patients but can affect relatively young adults. Chondrocalcinosis (calcification of cartilage) may be present. The knee (meniscus), synphysis pubis (disk), and wrist (triangular fibrocartilage) are common locations for chondrocalcinosis. Bone minerals are typically preserved. Large osteophytes and uniform joint-space narrowing can be observed. Findings of large osteophytes in non–weight-bearing joints, such as the glenohumeral and patellofemoral joints, should raise the possibility of pyrophosphate arthropathy.
Seronegative Spondyloarthopathies  
Seronegative arthropathies include ankylosing spondylitis, sacroiliitis associated with inflammatory bowel disease, psoriatic arthritis, and reactive arthritis. The unifying radiographic manifestation is enthesitis—chronic inflammation at the tendon/ligament insertion. Erosions initially occur at the capsular insertion followed by bony proliferation (sclerosis and bony outgrowth) (Figure 4). Ankylosis may eventually occur.

Neuropathic Arthropathy  
Chronic repetitive trauma in a joint with poor sensibility may explain some of the radiographic changes of neuropathic arthropathy, but the exact pathogenesis is not clear. The radiographic changes include the wide spectrum of bony changes from total bony resorption (an atrophic neuropathic joint) to excessive repair (a hypertrophic neuropathic joint). The hypertrophic changes show the classic pattern of joint destruction, dislocation, debris, and excessive bone formation. In the foot and ankle, diabetes mellitus is the most common cause of neuropathic arthropathy, typically involving the midfoot and forefoot. Septic joint and osteomyelitis are often difficult to exclude in patients with a neuropathic joint.

Neoplasms  
Diagnosing bone tumors is primarily based on the patient’s history (age and symptoms) and the radiographic findings. The tumor location, border (for lytic lesions), periosteal reaction, and matrix calcifications should be evaluated. Cross-sectional imaging with CT and MRI may be used to confirm the radiographic findings and provide additional information such as the cystic nature of the lesion (fluid-fluid levels or peripheral enhancement after intravenous contrast) and the extent of the tumor. Clinically important distinctions between benign and malignant tumors rely mainly on radiographic findings. Without radiographic correlation, MRI findings alone can be misleading in diagnosing certain benign lesions such as osteoid osteoma, osteoblastoma, chondroblastoma, and eosinophilic granuloma. In such instances, the appearance of the lesion on MRI scans may suggest an aggressive tumor.
Radiography is generally not helpful in diagnosing soft-tissue tumors. Radiography may detect calcification (for example, in synovial cell sarcomas), phleboliths (for example, in hemangiomas), and hyperostosis at the adjacent bone (associated with benign soft-tissue lesions). Cross-sectional images provide information about the location and size of a lesion and its relationship to the adjacent structures, especially neurovascular structures. Additional advantages of cross-sectional images include evaluation of fat content and cystic or solid nature of the lesions.

**Infections**

Radiography is less sensitive than other imaging modalities, such as bone scanning and MRI, for the early detection of acute osteomyelitis; however, radiography may show focal osteolysis and periosteal reaction in patients with acute osteomyelitis. A comparison with previous radiographs is important, especially for patients with diabetic foot infections in whom it can be difficult to differentiate between neuropathic osteoarthropathy and infection. Radiography is sensitive for detecting soft-tissue emphysema (Figure 5), which can be caused by a life-threatening infection.

**Metabolic Diseases**

Digital radiography automatically adjusts the amount of radiation in the field of view. Because a wide range of settings is available to review the digital images on the display monitor, the bone density, which is subjectively estimated by a digital system, can be misleading. Cortical thinning and accentuation of trabeculae can be assessed when considering the diagnosis of osteoporosis. Characteristic radiographic findings of rickets are often seen on a chest radiograph (Figure 6). Enlargement of the rib ends (rachitic rosary), widening of the proximal humeral physis, and subcortical bone resorption at the inferior scapular angles can be detected. Fragile osteopenic bones in patients with osteogenesis imperfecta usually lead to multiple fractures. Radio-
graphic features of rickets and osteogenesis imperfecta may overlap with those of child abuse.

**Congenital Anomalies**

Radiography can be used in the diagnosis of certain congenital bony anomalies. Congenital dislocation of the radial head may be an isolated abnormality or may be associated with other conditions such as scoliosis or Klippel-Feil and nail-patella syndromes. Radial head dislocation is associated with a small, dome-shaped radial head and hypoplastic capitellum (Figure 7). Congenital pseudarthrosis of the clavicle almost always occurs in the right clavicle. Radiographically, the middle segment is partially missing with tapering of the medial segment (Figure 8). These congenital anomalies can potentially be misdiagnosed as a posttraumatic condition. A standing PA view of the entire spine is obtained on a single image for the evaluation of scoliosis. The PA projection reduces radiation exposure to the breast and thyroid by threefold to sevenfold compared with the AP projection. Lateral radiographs may be obtained after scoliosis is diagnosed to assess sagittal alignment.

**Computed Tomography**

**Recent Advances in Technology**

Substantial advances in CT technologies have occurred in the past two decades. Helical CT was commercially introduced in 1988 and multidetector CT (MDCT) technologies were introduced in 1992. In a single-detector helical CT, detectors are aligned along the patient’s axial plane (x-y plane). With MDCT, detectors are also stacked along the long axis (z-axis), enabling collection of large amounts of data per each x-ray tube rotation. Increasing the speed of the x-ray tube rotation (to 0.5 to 0.35 seconds/rotation) contributed to further reduction of total scanning time. CT scanners with 64
detectors have been installed in many facilities, and scanners with 320 detectors became commercially available in 2008. With MDCT, the emitted x-ray beam is more efficiently used than before, thus contributing to a reduction in the radiation dose.

MDCT is capable of generating multiple thin slice images (reconstructed images) from large volumetric data sets. With this technology, hundreds of axial images are usually generated with each study. The images are reviewed as a volume rather than as individual axial images. Three-dimensional workstations are necessary for viewing these large image data sets from which multiplanar reformatted images can be interactively reviewed in any chosen plane and are not limited to sagittal or coronal planes (Figure 9). Internet-based three-dimensional software can be easily accessed by multiple readers and may eventually replace three-dimensional workstations.

Fracture Imaging

Spine Fractures

The increased availability of CT has contributed to the recent change in indications for CT of cervical spine fractures in the emergency department. Because the time required to reach a correct diagnosis is a critical factor for managing multitrauma patients, CT has become an essential tool for ruling out or diagnosing cervical spine fractures. A recent survey has shown that 40% of emergency departments in the United States have CT scanners. Indications for cervical spine CT in high-risk patients were previously discussed in this chapter.

CT is recommended to assess spine trauma in patients with ankylosing spondylitis or diffuse idiopathic skeletal hyperostosis whose spines are rigid because of bony fusion. In patients with advanced ankylosing spondylitis, severe osteoporosis makes radiographic detection of a fracture less reliable (Figure 10). Fractures in an ankylosed spine are typically oriented transversely and affect all three columns. Multiplanar reformatted images clearly delineate such fractures, which are difficult to detect on axial images.

Because CT allows poor visualization of ligaments compared with MRI, it is debated whether CT alone
can be used to exclude cervical spine injuries. However, studies have shown that pure ligamentous injuries without fractures are uncommon.13 Studies on ruling out cervical spinal injuries in obtunded patients have shown that CT, in comparison with a composite reference standard (subsequent imaging and clinical examinations) or with MRI, has a 99% negative predictive value for ruling out ligamentous injuries and a 100% negative predictive value for ruling out unstable cervical spine injuries.14,15

In the thoracic and lumbar areas of the spine, most fractures occur at the fulcrum of motion between T11 and L2. These fractures account for approximately 50% of all spinal fractures. In multitrauma patients imaged with MDCT of the chest, abdomen, and pelvis, spine CT images can be reconstructed without additional scanning. CT body studies using a 2.5-mm detector collimation and reconstructed spinal CT images have shown high accuracy in depicting thoracic and lumbar spine fractures.16,17 Single-pass, whole-body scanning can be used to cover an extended area from the head to the pelvis. This method contrasts with the segmented approach because there is no overlap between the irradiated fields.18,19

Pelvic and Acetabular Fractures
Because of the complex anatomy of the pelvis, conventional radiography often fails to show the full extent of a fracture, the spatial relationship of the major fracture fragments, and the intra-articular bony fragments. Specific indications for CT include acetabular fractures, sacroiliac joint involvement, and sacral and lumbosacral junction injuries.20

Approximately 30% to 40% of pelvic injuries involve the acetabulum.21,22 The Letournel classification is based on AP and oblique (Judet) pelvic radiographs. CT is routinely performed to aid preoperative planning. Standard pelvic radiographs add little information to CT scans in classifying acetabular fractures; however, standard radiographs are still important for intraoperative assessment and follow-up evaluation.

Fractures of the Extremities

Wrist Fractures
Traditionally, clinically suspected scaphoid fractures are treated with immobilization and followed clinically and radiographically regardless of the initial radio-
graphic findings. To improve cost-effectiveness and speed a patient’s return to function, more sensitive imaging modalities such as bone scans, MRIs, and high-spatial-resolution ultrasound studies are now commonly used.\textsuperscript{24-30} CT has been used to detect occult fractures of the wrist when radiographs are negative.\textsuperscript{25,31} There have been case reports of scaphoid fractures diagnosed by bone scanning and/or MRI but missed by CT.\textsuperscript{32,33}

**Elbow Fractures**
Complex fractures or fracture-dislocations of the elbow can be difficult to characterize by radiography alone, especially after cast immobilization. CT can clearly show the relationship between multiple bony fragments when reviewed on multiplanar reformatted images along the humerus, radius, and ulna and on three-dimensional images (Figure 11).

**Tibial Plateau Fractures**
Studies of CT using multiplanar reformatted or three-dimensional imaging have shown that using CT scans in addition to radiographs changes an observer’s classification of a tibial plateau fracture in 12% to 55% of cases compared with using radiographs alone; the use of both imaging modalities also results in treatment modifications in 26% to 60% of patients.\textsuperscript{34-37} CT is an excellent modality for assessing comminution in a tibial plateau fracture and the amount of depression of the articular fragments, and is helpful in preoperative planning.

**Ankle Fractures**
Radiographic studies may underestimate the size and displacement of a posterior malleolar fracture. A report of 57 surgically treated patients with a posterior malleolar fracture showed a wide variation in fracture orientation and that approximately 20% of the fractures extended to the medial malleolus.\textsuperscript{38}

**Calcaneal Fractures**
In the mid 1990s, CT was shown to allow excellent visualization and evaluation of the pathoanatomy of intra-articular calcaneus fractures with direct axial and coronal scans.\textsuperscript{39} Since that time, CT with multiplanar reformatted imaging and three-dimensional imaging has become the standard investigative modality to guide the treatment of intra-articular fractures of the calcaneus.\textsuperscript{40} Using isotropic imaging, single scanning through the calcaneus is sufficient to evaluate the integrity of subtalar and calcaneocuboid joints. Volume rendering to visualize tendon-bone relationships has been introduced and clinically applied to evaluate the tendons in the ankle and foot\textsuperscript{41} (Figure 12).

**Postoperative Complications**
The use of CT in patients with orthopaedic hardware can be hampered by severe metal artifacts. Metal artifacts are displayed on CT scans as streak or sunburst artifacts, which degrade the image quality. With proper data acquisition, image reconstruction, and image reformatting, diagnostic CT scans can be obtained for most patients. Prostheses made of a cobalt-chromium alloy cause substantial artifacts, whereas titanium implants produce less significant metal artifacts. The use of multiplanar reformatted imaging helps to decrease the adverse effects of metal artifacts on image quality. Three-dimensional volume rendering is also helpful in reducing streak artifacts associated with hardware.\textsuperscript{42,43} Postoperative CT may be performed to evaluate intra-articular fracture reduction and hardware placement. In the spine, pedicle screw misplacement can be associated with neurologic complications. CT has been reported to be 10 times more sensitive than radiography for detecting medial pedicle cortex violations.\textsuperscript{44} Recently developed three-dimensional C-arm CT scanning with flat-panel detectors has been introduced into orthopaedic practices.\textsuperscript{45} C-arm CT has been used to intra-
operatively assess spinal fusion and pedicle screw placement.

Failure of Bony Fusion
Radiography is inaccurate in assessing bony fusion when compared with CT.\textsuperscript{46} Radiography may under-estimate or overestimate bony fusion in patients with fracture fixation or arthrodesis.\textsuperscript{46} In a recent investigation, CT was reported to be useful in predicting stability for patients with ankle or subtalar arthrodesis.\textsuperscript{47}

Following surgery for spinal fusion, the assessment of the bony fusion with flexion and extension lateral radiographic views may be useful for the gross evaluation of instability. Sagittal and coronal reformatted CT images through the fusion site are best for evaluating bone bridging and the integrity of the fusion mass.\textsuperscript{48}

Osteolysis
Radiographic detection of osteolysis can be influenced by the patient’s body habitus, the position of the hardware, and the location of the lesion. Radiography can provide limited information, even with multiple projections, on the location and amount of osteolysis. Fluoroscopically guided radiographs may be indicated to obtain true tangential views of components in total knee replacements.\textsuperscript{49} CT may be indicated not only for the detection of osteolysis but also for the evaluation of bone loss before surgery.\textsuperscript{50-52}

Hardware Problems
Hardware fractures may be detected on CT scans and are usually associated with other complications such as nonunion and osteolysis (Figure 13). The position of the component, subsidence of the component, and polyethylene wear following hip or knee arthroplasty are usually assessed on radiographs. CT can be used to detect polyethylene liner dislocations. Patellofemoral symptoms may be associated with component malrotation. CT is the study of choice to evaluate rotational malalignment of the femoral and tibial components in total knee arthroplasty.\textsuperscript{53,54}

The efficacy of CT in detecting hardware complications has not been well investigated. One study of 114 CT imaging studies from 109 patients used clinical or surgical outcomes as the reference standard and measured sensitivity, specificity, and positive and negative predictive values of CT (74%, 95%, 88%, and 88%, respectively).\textsuperscript{55} Radiography alone was less sensitive in detecting hardware complications such as nonunion and osteolysis than was CT alone.

Magnetic Resonance Imaging

Advantages and Limitations
Because of its excellent soft-tissue contrast, MRI has become the diagnostic modality of choice for evaluating bone marrow, cartilage, and soft tissues; the absence of ionizing radiation also makes it an ideal mo-
dality for imaging in children. Limitations of MRI include the relatively long scanning time, which necessitates the use of sedation or general anesthesia in young children and uncooperative adults. MRI cannot be used in patients with cochlear implants or a pacemaker, and may not be useable in some patients with certain orthopaedic metal implants that are located in close proximity to the area being scanned. Fortunately, most modern orthopaedic implants are nonferromagnetic and will not displace when the patient is within a strong magnetic field. When an implant is suspected of being ferromagnetic, an identical implant can be tested with a horseshoe magnet before MRI. In practice, most radiology departments try to obtain the specific manufacturer’s part number and check for magnetic resonance compatibility. Specific absorption rate (SAR) is related to the amount of tissue heating resulting from radiofrequency pulses. Modern scanners typically estimate the SAR values and will suggest protocol changes to reduce SAR values to safe levels. SAR increases at higher field strengths, which may require adjustments to the imaging protocol such as increasing the repetition time or reducing the number of slices. Most metal implants produce susceptibility artifacts, rendering the images nondiagnostic for abnormalities close to the metal implants. Ideally, the radiologist should be notified in advance about the presence of a metal implant in the area of interest; a special MRI sequence can then be prescribed that can reduce, but not completely eliminate, metal artifacts.

MRI Sequences
Orthopaedic surgeons should be familiar with the capabilities of commonly used MRI sequences. T1-weighted sequences take a short time to acquire and are excellent for the initial investigation of any disease process in

![Figure 14](image-url)
bones, joints, or soft tissues. T1-weighted sequences show good anatomic detail and are highly sensitive for detecting marrow abnormalities such as infiltrative processes, metastases, or infections\(^5\) (Figure 14). A T1-weighted sequence is often the only sequence needed to diagnose an occult fracture of the hip in elderly patients or metastases in the spine. Most abnormalities have low signal intensity on a T1-weighted sequence.\(^5\)

T2-weighted sequences are ideally suited for diagnosing pathologic processes. When fat suppression is added to T2-weighted sequences, all fat-containing tissues appear black. Fat suppression is useful in accentuating the difference in contrast between normal and abnormal tissues. T2-weighted sequences are water sensitive; therefore, a bright signal is displayed for lesions containing water, such as bone marrow edema (Figure 15), soft-tissue edema, tumors, infections, abscesses, and acute fractures.

Proton density-weighted sequences (also known as intermediate-weighted sequences) have a high signal-to-noise ratio and reveal exquisite anatomic detail. Fat-suppressed proton density sequences have been used, with excellent results, for imaging articular cartilage.

A short-tau inversion recovery (STIR) sequence is also a water-sensitive sequence. This sequence suppresses the signals from fat much like the fat-suppressed T2-weighted sequences; however, it has two advantages over the fat-suppressed T2-weighted sequences. STIR sequences uniformly suppress fat over a large field of view, which is often not the case with fat-suppressed T2-weighted sequences. Metal artifacts are significantly less pronounced with a STIR sequence than with other sequences, although STIR imaging has a lower signal-to-noise ratio than the fat-suppressed sequences.

Gradient-echo sequences also have advantages for some applications, and typically a short acquisition time. Some gradient-echo sequences are good for imaging articular cartilage because articular cartilage can be distinguished from intra-articular fluid by assigning slightly different signal intensity to each. Gradient-echo sequences also are useful when scanning for hemosiderin in lesions such as pigmented villonodular synovitis. The three-dimensional fat-suppressed spoiled gradient-echo sequence in the steady state and the three-dimensional gradient-echo double excitation sequence in the steady state have been successfully used for cartilage imaging\(^5\) (Figure 16).

**Contrast Agents for MRI**

Gadolinium compounds have been used in musculoskeletal imaging for approximately 20 years and can be used intravenously to evaluate synovial inflammation, vascular lesions, neoplasms, and abscesses. Gadolinium is useful in differentiating a neoplasm from a cyst because the neoplasm enhances after an intravenous injection of gadolinium, whereas the cyst does not enhance. This contrast agent can be used to differentiate a drainable abscess from a phlegmon because pus within the abscess will not enhance, whereas the entire phlegmon will enhance (Figure 17). It also can be used to assess the extent of necrosis within a tumor. Such information is helpful in planning a biopsy because the necrotic tissue can be avoided and the biopsy needle can be directed at the enhancing tissue. The recommended dose for gadolinium is 0.1 mmol per kg of body weight. Re-
cently, gadolinium was shown to cause serious adverse effects in patients with impaired renal function; a potentially lethal disease known as nephrogenic systemic fibrosis developed in some patients.60

Diluted gadolinium (1:100) is frequently used as an intra-articular contrast agent before magnetic resonance arthrography. It clearly delineates intra-articular abnormalities such as labral tears, recurrent meniscal tears, and cartilage defects. Despite the widespread use of gadolinium as an intra-articular contrast agent, the FDA has not approved its use for this purpose.

Recent Advances in Technology
In 2003, 3-Tesla (3-T) MRI began to achieve more widespread use as a clinical tool for musculoskeletal imaging. Because of the delay in creating dedicated coils for the different joints, the impact of the 3-T magnet on musculoskeletal imaging has been less dramatic than in other systems, such as the nervous system. The advantage of the 3-T magnet is in its high signal-to-noise ratio, which provides the potential for improved diagnostic confidence. There is little evidence, however, to show that 3-T MRI provides better diagnostic accuracy compared with 1.5-T MRI in diagnosing anterior cruciate ligament tears, meniscal tears, or shoulder abnormalities. Current clinical experience suggests that the higher signal-to-noise ratio enhances the visualization of ligaments and articular cartilage in small structures such as the hand and wrist.61

Isotropic data sets on 100 consecutive shoulder examinations were acquired after the injection of diluted gadolinium into the joint.62 An isotropic gradient-echo sequence and thin sections (0.4 mm) were used. With arthroscopy as the reference standard, 3-T MRI was reported to be accurate in assessing rotator cuff tears and labral tears.62 The authors of another study used isotropic MRI to study internal derangement of the knee with a three-dimensional fast spin-echo sequence.63 Initial results from this study on knees of healthy volunteers were promising.

Occult Fractures
The most common lawsuit filed against emergency department physicians involves missed orthopaedic injuries. In the past two decades, MRI has become an important tool for diagnosing injury in trauma patients in the emergency department. MRI is particularly useful in evaluating suspected occult fractures (those not initially seen on radiographs) and for ruling out ligamentous injuries in the cervical spine of obtunded patients. Common sites for occult fractures are the femoral neck, scaphoid bone, tibial plateau, and talar neck.

Hip radiography has more than a 90% sensitivity for detecting fractures; however, approximately 3% to 4% of patients present with occult hip fractures. Current evidence favors MRI as the best modality for detecting these occult fractures. Coronal T1-weighted images of the hip typically show a dark line at the fracture site (Figure 15). Studies have reported that a T1-weighted sequence is sufficient for diagnosing occult hip fractures.64

Occult scaphoid fractures can be challenging to diagnose, and delayed treatment increases the risk of complications. There is mounting evidence to suggest that MRI is the modality of choice for detecting occult scaphoid fractures.65

Cervical Spine Injuries
Cervical spine injuries occur in approximately 2% to 6% of patients with blunt trauma; there is a real potential for a catastrophic neurologic deficit if such injuries are undiagnosed. In an alert trauma patient without a distracting injury, the cervical spine can be clinically cleared provided the neurologic examination is negative and the cervical spine has full range of motion and is without pain or tenderness. In the obtunded or unreliable patient, the optimal approach for ruling out cervical spinal injury has not yet been determined. The possibility of an unstable ligamentous injury is a troubling consideration in the obtunded patient and is the reason...
for further imaging after a negative CT examination to confirm intact ligamentous structures. The use of lateral flexion and extension views with fluoroscopy was briefly advocated, but was judged too hazardous and has been replaced with MRI. Recently, several investigators have reported that MDCT alone is sufficient for clearing the cervical spine. Because MDCT cannot be used to image spinal ligaments or the spinal cord, MRI continues to be recommended by some authors to rule out unstable ligamentous injuries of the cervical spine in obtunded patients. However, transporting an obtunded patient from the intensive care unit to the MRI suite is a difficult task and involves risks for the patient.

A retrospective review of 366 obtunded patients whose cervical spines were evaluated with both CT and MRI showed that 12 patients (3.3%) had cervical spine injuries that were not detected by MDCT; however, none of the injuries were unstable and none of the patients required surgery. It was concluded that MDCT has negative predictive values of 98.9% for detecting ligamentous injuries and 100% for detecting unstable injuries. Another review of 202 patients initially evaluated with CT followed by MRI showed that MDCT continues to miss both stable and unstable cervical spinal injuries. Of 18 patients (8.9%) who had abnormal MRI examinations, 2 required surgical spinal repairs, 14 required extended use of a cervical collar, and the cervical collar was removed in 2 patients at the discretion of the attending surgeon. It was concluded that MRI changed treatment management in 7.9% of patients with negative MDCT examinations. The continued use of MRI for cervical spine clearance in the obtunded or unreliable patient was recommended by the study authors. However, recent evidence supports the belief that MRI is unlikely to uncover unstable cervical spine injuries in obtunded patients when a late-generation MDCT examination is negative.

Spinal Cord Injury Without Radiographic Abnormalities

The acronym SCIWORA was coined in 1982 for describing the presence of spinal cord injury without radiographic abnormality in children. After MRI became widely available for assessing spinal cord injuries, the term SCIWORA became somewhat ambiguous.
A 2008 literature review performed to clarify this ambiguity, it was recommended that if any pathology is detected on MRI, with or without radiographic abnormality, the classification of SCIWORA should not be used for the patient.68 It was also recommended that the label and meaning of SCIWORA be changed to reflect the concept of spinal cord injury without neuroimaging abnormality. A 2004 study also recommended the importance of considering MRI findings before using the SCIWORA classification for a patient.69

**Nuclear Medicine**

The most common radionuclide studies in musculoskeletal imaging are bone scans and positron emission tomography (PET) scans. Bone scans are performed using technetium-Tc 99m-labeled phosphonates (Tc-99m methylene diphosphonate [MDP], Tc-99m hydroxyethylidene diphosphonate). After intravenous injection, approximately one third of the injected dose of Tc-99m MDP localizes in the bone within 2 to 4 hours. Tc-99m emits gamma photons with a half-life of 6 hours. The gamma photons are detected by a gamma camera to produce images reflecting the distribution of the radiopharmaceutical. Tc-99m—labeled phosphonates accumulate preferentially in areas of active bone formation. As a result, areas of increased bone remodeling caused by tumor, infection, trauma, or metabolic bone disease appear “hot” on a bone scan. Therefore, bone scan abnormalities may not be specific for a disease process and should be interpreted in conjunction with the clinical history and other imaging modalities. Bone scans are routinely done 2 to 4 hours after injection of the radiopharmaceutical. Whole-body bone scans are used for screening the entire skeleton for metastatic bone disease. Single photon emission CT (SPECT) provides imaging in transaxial, coronal, and sagittal tomographic scans and is particularly helpful for evaluating the spine.

PET uses radiopharmaceuticals that are labeled with positron emitters. The most commonly used radiopharmaceutical in clinical PET is fluorine-18 deoxyglucose (FDG), which is a glucose analog labeled with fluoride-18, with a half-life of 110 minutes. FDG-PET is primarily used in staging and restaging of malignancies. FDG shows increased accumulation in cancer cells because of enhanced transport of glucose and an increased rate of glycolysis in tumors. Most PET imaging currently is done on integrated PET-CT scanners. The CT portion of PET-CT is used for localization of metabolically active lesions but also may be used to obtain diagnostic-quality CT scans. FDG-PET scans are performed 60 to 90 minutes after injection of the radiopharmaceutical. FDG-PET scans should not be obtained in patients with uncontrolled diabetes because high glucose levels reduce the uptake of FDG in tumors.

**Occult Fractures and Stress Fractures**

Bone scans are highly sensitive for diagnosing occult fractures in symptomatic patients with negative radiographs. Bone scans are most often done to evaluate fractures in the wrist, hips, and spine; the scans are positive in 90% to 95% of fractures within 24 hours of the traumatic event. In elderly patients, bone scans may be negative in the initial 24 hours; therefore, repeated imaging at 72 hours is recommended if the initial bone scan is negative.70 Bone scans may remain positive for up to 3 years after a fracture because of persistent bone remodeling.71

Bone scans also can be helpful in diagnosing stress fractures. These fractures may not be initially identified on plain radiographs. A negative bone scan excludes the presence of a stress fracture.72 A long-bone stress fracture on a bone scan shows focal fusiform increased uptake at the site of injury (Figure 18). Bone scintigraphy also is useful in differentiating stress fractures from shin splints. Shin splints typically refer to tibial perios-
titis and usually require a shorter recovery period than stress fractures. The typical appearance of shin splints is linear uptake along the posteromedial aspect of the middle third of the involved tibia.

Spondylolysis refers to a bone defect in the pars interarticularis of a vertebra, most commonly at L4 or L5, and is believed to occur as a result of a stress fracture. Patients with spondylolysis may be asymptomatic; in such instances, the condition may be diagnosed as an incidental imaging finding. However, in some patients, spondylolysis causes severe low back pain. A positive bone scan with focal uptake in the pars region indicates that the spondylolysis may be the cause of low back pain and correlates with a good outcome after fusion surgery. SPECT images of the lumbar spine always should be obtained because more than 50% of active spondylolysis may not be detected with routine planar bone scans (Figure 19). Bone scans should be interpreted in correlation with radiographs and/or CT scans because other conditions such as infections, osteoid osteomas, and tumors may also be positive on bone scintigraphy.

Infection
After a negative radiograph, a three-phase bone scan is considered a good choice for diagnosing osteomyelitis. The typical findings of acute osteomyelitis on a bone scan are focal increased flow and focal increased uptake of the tracer on the delayed bone scan phase. In patients with no prior fracture or hardware, a three-phase bone scan is highly accurate for diagnosing osteomyelitis, with a sensitivity and specificity of more than 90%. Increased bone tracer uptake may be seen after a fracture, surgery, or hardware placement. In these patients, labeled white blood cell (WBC) scans are needed to complement the bone scans for diagnosis of osteomyelitis.

Labeled WBC scans are considered the primary imaging modality for assessing osteomyelitis in trauma patients with metallic implants or in patients with prosthetic joints. WBC scans can be labeled with indium-111 (In-111) or Tc-99m. Labeled WBCs do not show significant accumulation at surgical sites or fractures in the absence of infection. Labeled WBCs, however, accumulate in the bone marrow. Therefore, WBC scans need to be complemented with bone marrow scans if active marrow distribution is altered as a result of surgery, hardware, or diabetic osteoarthropathy. In osteomyelitis, there is an increased accumulation of labeled WBCs, which is incongruent with the bone marrow distribution delineated on Tc-99m sulfur colloid bone marrow scans (Figure 20). The sensitivity and specificity of labeled WBC scans for osteomyelitis in the peripheral skeleton and prosthetic joints is between 83% and 89%.

Labeled WBC scans are less accurate for diagnosing spinal osteomyelitis because of intense uptake of labeled WBCs in normal bone marrow, and possibly because of the reduced delivery of labeled WBCs. Vertebral osteomyelitis may show decreased uptake of labeled WBCs (cold vertebra); however, this pattern is nonspecific and may also be seen with tumors, infarcts, compression fractures, and in Paget disease. MRI is the modality of choice for imaging spinal infections. If MRI cannot be used or is inconclusive, radionuclide studies, including gallium-67 and FDG-PET scans, may be helpful. The exact mechanism of gallium-67 accumulation in inflammation is not known but appears to be related to the increased vascular permeability and presence of iron-binding proteins such as lactoferrin and siderophores in inflammatory lesions. Gallium-67 is taken up in areas of bone remodeling and inflammation and may be inconclusive in a substantial group of patients. Although FDG-PET is primarily used in malignancy workup, substantial accumulation of FDG is also observed in infections because of increased glucose metabolism in activated neutrophils and macrophages. Experience using FDG-PET to diagnose infections is limited; however, the available data are encouraging, particularly as an alternative imaging

Figure 19 Imaging showing spondylolysis. A, Planar posterior bone scan image shows subtle uptake at L5 vertebra (arrow). Tracer uptake is clearly visualized on SPECT coronal (B), sagittal (C), and transaxial (D) bone scans, which localize the focus in the right pars region (arrows) of the L5 vertebra, consistent with a pars fracture.
modality in chronic osteomyelitis. In a recent meta-analysis that included four studies with FDG-PET, the sensitivity and specificity for diagnosing osteomyelitis was 96% and 91%, respectively.82 FDG-PET is promising in diagnosing spinal infections, with a reported sensitivity of 100% and specificity of 88%.78

Tumors

Whole-body bone scans are routinely used for surveillance of metastatic bone disease. The typical pattern of osseous metastasis is the presence of multiple focal areas of increased tracer uptake predominantly in the axial skeleton. Bone scanning is more sensitive than radiography for detecting metastatic bone disease. A notable exception is multiple myeloma, which does not induce a significant osteoblastic response and is better detected on radiographs. Osteosarcomas and Ewing sarcomas show intense tracer uptake on bone scans. The primary use of bone scans in osteosarcoma and Ewing sarcoma is for initial staging and follow-up of the disease. Many benign bone tumors and tumor-like lesions may also show intense tracer uptake on bone scans. Therefore, bone scans cannot be used to differentiate between benign and malignant lesions. Bone scans can be used to screen for polyostotic disease in fibrous dysplasia, enchondroma, and Paget disease. Bone scans are also highly sensitive for diagnosing osteoid osteoma in patients with chronic pain and negative radiographic results.83

FDG-PET is increasingly being used in sarcoma workups. In a recent study that included 160 soft-tissue sarcomas and 52 osseous sarcomas, the sensitivity of FDG PET was 94% for detecting soft-tissue sarcomas and 95% for osseous sarcomas.84 The sensitivity was 80% or greater for all histologic types, with false negative lesions seen in synovial sarcoma, liposarcoma, chondrosarcoma, and osteosarcomas. High-grade sarcomas generally have more intense FDG uptake than low-grade lesions; however, because of significant overlap, FDG-PET cannot be used to reliably grade sarcomas.85 False-positive PET scans can occur in several benign bone lesions, including giant cell tumors, fibrous
dysplasias, eosinophilic granulomas, chondroblastos-
mas, aneurysmal bone cysts, and nonossifying fibro-
mas. FDG-PET can be helpful in guiding the biopsy to
sample the metabolically active part of the tumor.

FDG-PET CT is highly accurate in staging sarcomas
(Figure 21). An 88% sensitivity was reported for PET
CT in nodal staging of 117 patients with sarcoma com-
pared with a 53% sensitivity for conventional imaging,
which included MRI, chest radiographs, whole-body
contrast-enhanced CT, and bone scans. PET CT was
also more sensitive for detecting distant metastases,
with a sensitivity of 92% compared with 65% for con-
ventional imaging. These findings were confirmed in a
multicenter prospective study, which included 46 pedi-
atric patients with osteosarcoma, Ewing sarcoma, or
rhabdomyosarcoma. The sensitivity of PET is limited
in diagnosing lung metastases, particularly for lesions
smaller than 1 cm; however, those lesions can be diag-
nosed on the CT component of the PET CT scan. FDG-
PET CT was also found to be useful in detecting recur-
rent metastatic disease after therapy.

The use of FDG-PET CT also has been investigated as
a tool in evaluating the chemotherapy response in pa-
tients with sarcomas. In one study, the change in FDG
uptake between baseline and post therapy PET scans was
found to be a significantly better predictor for evaluat-
ing the response to neoadjuvant therapy than the change
in lesion size. Large multicenter trials are needed to fur-
ther define the role and criteria for PET in assessing re-
sponses to chemotherapy in sarcoma patients.
Interventional Procedures

Needle Biopsy

Percutaneous needle biopsies have been a safe and accurate procedure for more than 70 years. For primary bone tumors and soft-tissue sarcomas, a core needle biopsy is preferred over fine-needle aspiration. Core needle biopsy is better for determining the cell type and tumor grade.92 For metastatic lesions and round cell sarcomas, fine-needle aspiration can suffice. Currently, most bone biopsies are performed with CT guidance, whereas soft-tissue tumors are biopsied with ultrasound guidance. In the past decade, CT fluoroscopy was introduced to assist in real-time positioning of the needle; its value has been documented in thoracic and abdominal lesions. Using CT fluoroscopy in the biopsy of musculoskeletal lesions achieved similar or better results than conventional CT. However, the high ionizing radiation exposure to both the patient and operator are an important risk factor in using this technique.

Recently, MRI-guided percutaneous biopsies for musculoskeletal lesions have been attempted.93 Indications include the need to improve the lesion conspicuity when it is not well seen by other imaging techniques or when the lesion is adjacent to critical structures that are better visualized with MRI. The open-configuration magnet has been recommended for interventional procedures because it provides better access to the patient. Results in one study ranged from very good for bone lesions to moderate and fair for soft-tissue lesions.93

Three to four biopsy cores are usually sufficient for arriving at a pathologic diagnosis. Most biopsies are performed under local anesthesia. Less than one third of adult patients require conscious sedation. General anesthesia is reserved for young children and uncooperative adults. For primary bone tumors, it is recommended that the approach and needle route be discussed with the orthopaedic tumor surgeon. If the tumor has a necrotic center, it should be avoided and the biopsy cores should be cut from the periphery of the lesion. The main drawback of a needle biopsy is the possibility of a false-negative result because the accuracy of a negative result can be established only by follow-up or by open biopsy. The diagnostic yield is higher in lytic than in sclerotic lesions, in larger lesions, and in those with increased core length. Nondiagnostic cores tend to occur with benign lesion.

Percutaneous Radiofrequency Ablation for Osteoid Osteoma

Osteoid osteoma accounts for about 12% of all benign bone tumors. Although spontaneous resolution has been reported, pain may persist for years and patients often seek definitive treatment. Over the past decade, radiofrequency ablation (RFA) has become the treatment of choice for osteoid osteomas. The technique involves the introduction of an electrode through a biopsy needle into the lesion to heat the abnormal tissue and produce cell death. The tip of the electrode is heated to approximately 90°C for 4 minutes. Most of the experience with RFA is in the lower extremity where most osteoid osteomas occur (Figure 22). Lesions that do not allow a safe distance between the electrode tip and a major neurovascular structure may require surgical excision. This is true for the spine, hand, and carpus. However, some investigators have found RFA for spinal lesions to be safe and effective.94 The cost of RFA is estimated to be approximately 25% of the cost of open surgery.

Summary

Current imaging techniques and the indications for various orthopaedic conditions have been discussed along with characteristic imaging features. Working knowledge of imaging studies is important for orthopaedic surgeons to provide quality patient care.

Annotated References


   The authors describe current technologies of digital radiography compared with conventional screen-film systems. Image acquisition to establish image quality standards is discussed.


   The authors describe current technologies of digital radiography to provide high-quality radiologic care. Image processing and display are discussed. The management of data may have a great impact on the quality of patient care.


7. Lomoschitz FM, Blackmore CC, Mirza SK, Mann FA: Cervical spine injuries in patients 65 years old and older: Epidemiologic analysis regarding the effects of age


The authors review radiographic features of several types of arthritis emphasizing the radiographic differentials in degenerative joint disease and its variations.


The authors review the radiographic features of several types of arthritis emphasizing the radiographic differentials in inflammatory conditions.


A snapshot of the demographics of current imaging practices in emergency departments in the United States is presented. The study is based on the responses to an e-mail survey from 192 (28%) of contacted radiology groups.


A retrospective review of 12 patients with ankylosing spondylitis and 18 patients with diffuse idiopathic skeletal hyperostosis reported complete neurologic deficits in 41% of patients with ankylosing spondylitis and 28% of those with hyperostosis. Level of evidence: III.


Based on this retrospective cohort study of 367 obtunded patients, initial cervical CT failed to identify an injury in one patient, resulting in a false-negative rate of 0.3%. The upright radiographs did not show any additional injuries for all study patients. Level of evidence: II.


For multitrauma patients, whole-body, single-pass CT protocol in 26 patients was compared with conventional segmented protocol in 20 patients to define scanning time, image quality, and radiation dose. The whole-body protocol showed a reduced total radiation dose with no relevant loss of diagnostic image quality.


The authors retrospectively reviewed and compared the outcomes among the patients with acetabular and pelvic ring fractures (1,334 patients with 320 acetabular, 826 pelvic ring, and 188 combination fractures). Level of evidence: II.


A preliminary study consisting of 32 patients with acute calcaneal fractures showed that viewing three-dimensional volume-rendered images is more time-efficient compared with reviewing multiplanar reformatted images for detecting peroneal tendon dislocation. Level of evidence: III.


The authors of this study, based on the retrospective review of 42 consecutive CT studies from 29 patients, reported that ankle or subtalar fusion is likely stable if more than 33% of the joint has bone fusion on sagittal CT images. Level of evidence: III.

48. Shah RR, Mohammed S, Saifuddin A, Taylor BA: Comparison of plain radiographs with CT scan to evaluate interbody fusion following the use of titanium interbody


A retrospective review of seven patients with nephrogenic systemic fibrosis showed that symptoms of the condition developed in all of the patients after receiving gadolinium and all had renal failure. The authors found an association between the use of gadolinium in patients with renal failure and the development of nephrogenic systemic fibrosis.


The authors used a 3.0-T magnet with three different spin-echo sequences to study the visualization of normal and abnormal finger A2 pulley. They found that transverse fat-saturated T1-weighted gadolinium-enhancement sequences are best for depicting an abnormal A2 pulley.


The author presents the results of a retrospective review of 100 consecutive shoulder MR arthograms studied by standard T1-weighted spin-echo sequences and by isotropic gradient-echo imaging using 0.4-mm thin sections. The author found that isotropic imaging provides the same clinical information as conventional imaging and can be acquired in less than 3 minutes.


In this prospective study, the authors compared isotropic three-dimensional fast spin-echo extended echo-train acquisition with two-dimensional fast spin-echo and two-dimensional fast recovery fast spin-echo for MRI of the knee. The authors reported that the three-dimensional fast spin-echo extended echo-train acquisition method acquires high-resolution isotropic data with intermediate- and T2-weighting that may be reformatted in arbitrary planes.


The authors report on a retrospective review of patients with blunt trauma who had cervical spine imaging with CT and MRI in the acute phase. Newer generation CT missed cervical spine injuries in unreliable patients. MRI findings changed treatment in 7.9% of patients. Two patients required surgical repair. The authors recommend using MRI for clearing the cervical spine in unreliable patients.
Section 1: Principles of Orthopaedics


The authors report on a retrospective review of 180 trauma patients who had a normal CT examination on admission along with a cervical spine MRI. In 38 patients (21.1%), the MRI showed acute traumatic findings; however, surgery was not needed and delayed instability did not develop. The authors concluded that MRI is unlikely to detect unstable cervical spine injuries when the CT examination is normal.


A literature review was undertaken to investigate whether the meaning of SCIWORA had changed after the advent of MRI. The authors found that SCIWORA had an ambiguous meaning in the literature. They recommended that spines with MRI abnormalities, with or without radiographic abnormalities, should not be classified as SCIWORA.


This large study evaluates the sensitivity of FDG-PET for detecting osseous and soft-tissue sarcomas with different histologies.


This retrospective study compares PET-CT with CT, MRI, and bone scans in staging osseous and soft-tissue sarcomas.


This prospective study evaluates the role of FDG-PET CT and its added value to conventional imaging in staging pediatric sarcomas.


The authors report on the role of FDG-PET CT in evaluating local recurrence at the primary site and distant disease in children with sarcoma.


The authors compare the change of FDG uptake (measured in standard uptake value) with the change in tumor size in predicting the response of sarcomas to chemotherapy.


The authors present an overview of approaches to bone biopsies intended to minimize potential tumor seeding into the soft tissues. They also discuss safe approaches related to specific anatomic parts.


In a retrospective case series of 45 biopsies performed with magnetic resonance guidance, the authors reported very good results for bone lesions, moderate results for extra-articular soft-tissue lesions, and fair results for intra-articular soft-tissue lesions.


The authors present the findings of a prospective study of 24 patients with spinal osteoid osteoma treated with RFA. The authors concluded that RFA is a safe and effective treatment for spinal osteoid osteoma. Surgery should be reserved for lesions causing nerve root compression.