Seminars in ULTRASOUND CT and MRI

Three-Dimensional CT and 3D MRI of Hip-Important Aids to Hip Preservation Surgery

Ajit Kohli, MD,[*] Shuda Xia, BS,[*] Joel E Wells, MD, MPH,[†] and Avneesh Chhabra, MD, MBA, FACR[*,‡,#]

Common hip internal derangements include femoroacetabular impingement (FAI), developmental dysplasia of hip (DDH) dysplasia, and avascular necrosis (AVN) of the femoral head. These are initially screened by radiographs. For preoperative planning of hip preservation, 3-dimensional (3D) CT is commonly performed to assess bony anatomy and its alterations. Magnetic resonance imaging (MRI) is used to evaluate labrum, hyaline cartilage, tendons, synovium, and loose bodies, and provides vital information for surgical decision-making. However, conventional 2D MRI techniques are limited by lack of isotropic multiplanar reconstructions and partial volume artifacts. With advancements in hardware and software, novel isotropic 3D MR Proton Density images are acquired with acceptable acquisition times leading to improved visualization of soft tissue and osseous structures for various hip conditions. Three-Dimensional MRI allows multiplanar non-gap reconstructions along the structures of interest. It results in detection of small, otherwise inconspicuous labral tears without the need for MR arthrogram, which can be subsequently measured. In addition, radial reconstructions of the femoral head can be performed from original 3D volume MR imaging and CT imaging without the need for individual different plane acquisitions. Three-Dimensional MRI thus impacts surgical decision-making for the important common hip derangement conditions. For example, femoral head hyaline cartilage loss may make hip preservation difficult or impossible. In this review, we discuss the advantages and technical details of 3D CT and MRI and their significant role in aiding hip preservation surgery for common hip conditions. The conditions discussed in this article include FAI, DDH, AVN, synovial disorders, cartilaginous tumors, and hip fractures.
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Key Points

1. Radiographs are most useful for initial cost-effective femoroacetabular impingement (FAI), developmental dysplasia of the hip (DDH), and femoral AVN screening.
2. Three-Dimensional CT of both hip and knee should be done to comprehensively and accurately evaluate hip measurements and femoral version.
3. Isotropic 3D MRI allows radial reconstructions of femoral head and neck junction, and a separate radial acquisition is not needed.

*Department of Radiology, UT Southwestern, Dallas, TX.
†Baylor Scott & White Comprehensive Hip Center and Associate Professor Texas A&M School of Medicine.
‡Department of Orthopedic Surgery, UT Southwestern, Dallas, TX.
AC: Consultant: ICON Medical and TREACE Medical Concepts Inc., Book Royalties: Jaypee, Wolters, Speaker: Siemens, Medical advisor and research grant: Image biopsy Lab Inc. JW: Consultant: Ethicon.
Address reprint requests to: Avneesh Chhabra, MD, MBA, Department of Radiology and Orthopedic Surgery, UT Southwestern, 5323 Harry Hines Blvd, Dallas, TX, 75390-9178. E-mail: avneesh.chhabra@utsouthwestern.edu
#Adjunct Faculty, Johns Hopkins University, University of Dallas, and Walton Centre for Neuroscience, UK

Introduction

The burden of musculoskeletal diseases in the United States is significant and has been increasing over the last several years. The proportion of the population reporting musculoskeletal conditions in the United States increased from 28% in 1996 to 1998 to 34% from 2012 to 2014, representing an increase of around 21%.[1] At present, musculoskeletal illnesses represent the most prevalent conditions in all age and sex groups starting in midlife. Hip disorders are one of the most frequent conditions and include developmental dysplasia of the hip (DDH), femoroacetabular impingement (FAI), fractures, avascular necrosis (AVN), synovial disorders, and cartilaginous tumors.

A wide variety of imaging modalities are used to evaluate hip conditions to guide conservative or surgical treatments with the goal of preserving the hip at younger ages. While ultrasound is commonly used in neonates for detection of DDH and hip effusion, radiographs represent the most common and cost-effective screening modality for most of the

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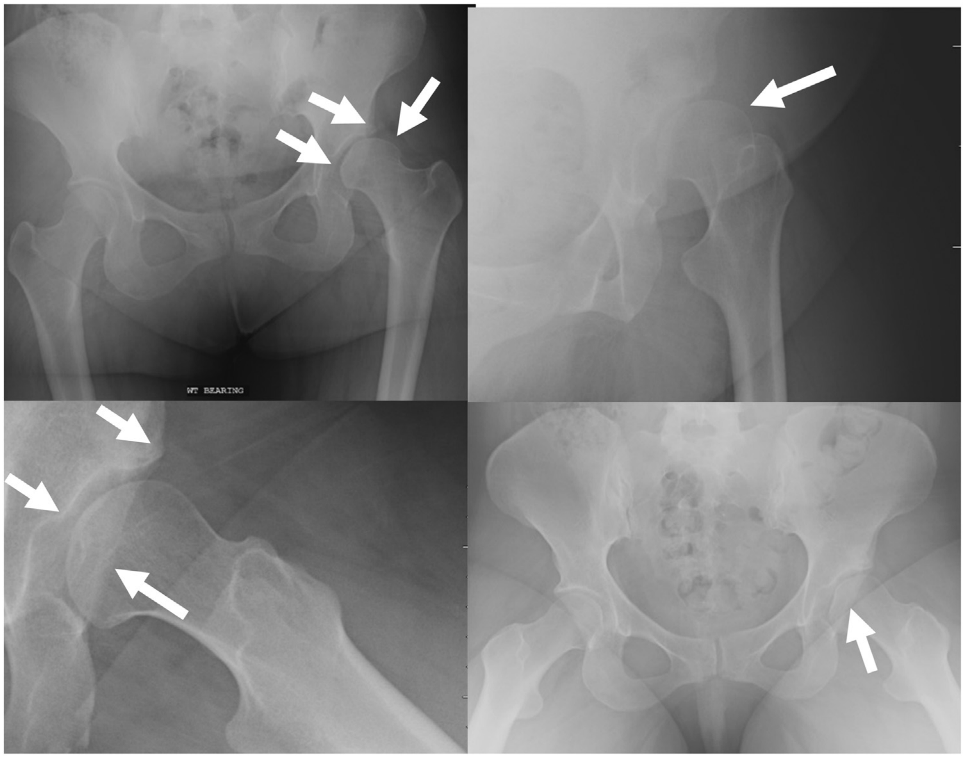

Figure 1 A 16-year-old female with a diagnosis of developmental dysplasia of the hip on the left side. Radiographs (standard 4-view series) show the abnormal anatomy of the hip joint with global dysplasia. Positive posterior wall sign and shallow anterosuperior acetabulum with superolateral subluxation of the left femoral head indicated by arrows.

above-mentioned disorders in all ages (Fig. 1). Three-Dimensional CT imaging is commonly used to define bone and joint anatomy prior to hip preservation surgery (Fig. 2) and MRI is used to assess soft tissue anatomy and pathology (Fig. 3).[2]

Management of above disorders initially includes conservative treatment, such as abductor strengthening and joint and bursal injections. Nonresponsive or recalcitrant cases may need hip preservation surgery via arthroscopy or surgical dislocation of the hip, for example, CAM resection and/or acetabuloplasty with labral repair for FAI, periacetabular osteotomy for DDH (Fig. 4), core decompression and vascularization for AVN, and synovectomy for synovial disorders.[3] If these fail, hemi- or total arthroplasty is needed to address the severely disabling conditions of the hip. Thus, the above imaging modalities are used as tools in guiding treatment, especially for deciding among the types of surgical interventions.[4]

MRI is currently the gold standard for evaluation of hip pathology. Conventional MRI is widely used to evaluate the bone marrow and soft tissue anatomy to assist with surgical decision-making and can take from 15 to 30 minutes to acquire the whole scan on the current scanners.[5] One major disadvantage of conventional MRI is that 2-dimensional imaging sequences are often obtained with a 10%-20% interslice gap and thicker slices, which results in smoother images with obscuration of fine details due to partial-volume artifacts.[6] In addition, these images cannot be reconstructed into other planes without significant artifacts. Thus, any specific plane, if desired, such as radial imaging, requires additional acquisition of a pulse sequence in that particular plane.

To address the above issues, 3D MRI sequences were developed. Older MR scanners only allowed 3D GRE sequences, which are subpar due to lower resolution, and susceptibility artifacts might degrade the images. Newer 3D fast spin echo (FSE) sequences are similar in contrast to the current 2D spin-echo joint sequences, which can be used to assess bone and soft tissues effectively. These sequences confer several advantages compared to 2D spin-echo sequences, such as a higher signal-to-noise ratio, better fluid-cartilage contrast, and improved differentiation and characterization of labrum, meniscus, and hyaline cartilage.[7] The 3D FSE imaging can be obtained in 0.7-0.9 mm resolution depending upon the patient's size, in an acceptable time period of around 5-6 minutes on newer 3-Tesla and 1.5 Tesla scanners. With recent software modifications, for example, using compressed sense, this isotropic imaging can be obtained in time as low as 4 minutes. The typical parameters of 3D intermediate weighted FSE imaging include TR = 1100ms, TE = 40ms, and voxel = 0.7-0.9 mm isotropic. With multiplanar reconstructions on 3D MRI, there is a better appreciation of labral tears, cartilage damage, and soft tissue degeneration in hip conditions, which can influence surgical decision-making.[8] Finally, due to volume acquisition, the specific planes of labrum or femoral head and neck for radial imaging, and bony modeling of hip can be generated without gaps or partial volume artifacts, just like 3D CT imaging.[5]

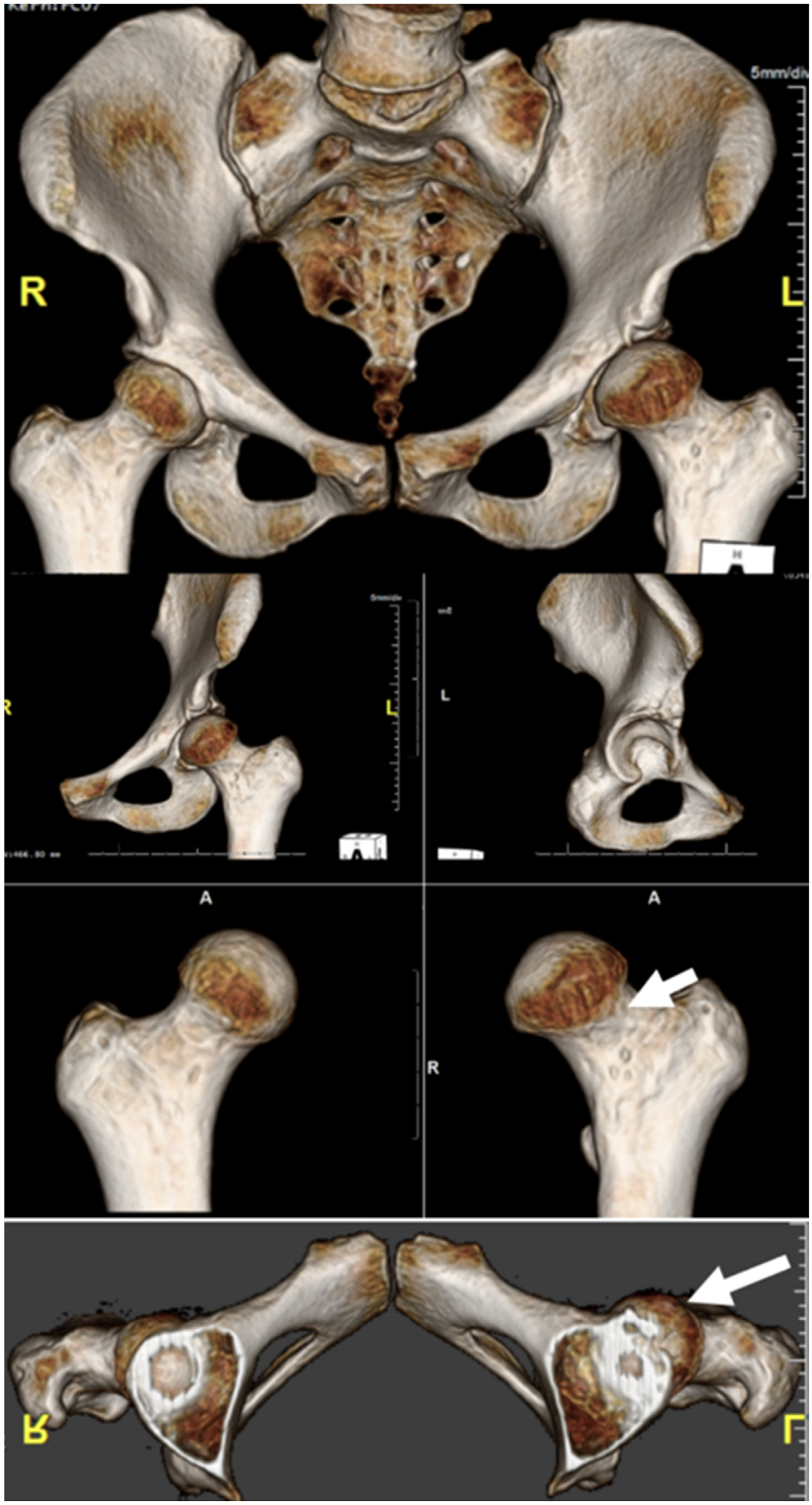

Figure 2 A 3D CT volume-rendered reconstructions of the hip from the same patient as in Figure 1 confirm global dysplasia of the left hip through visualization of the shallow acetabulum and incongruities in the femoral heads. Notice inferolateral head and neck bump (small arrow) and lateral extrusion of the femoral head on the top-down cut-out view (large arrow) (Color version of figure is available online.)

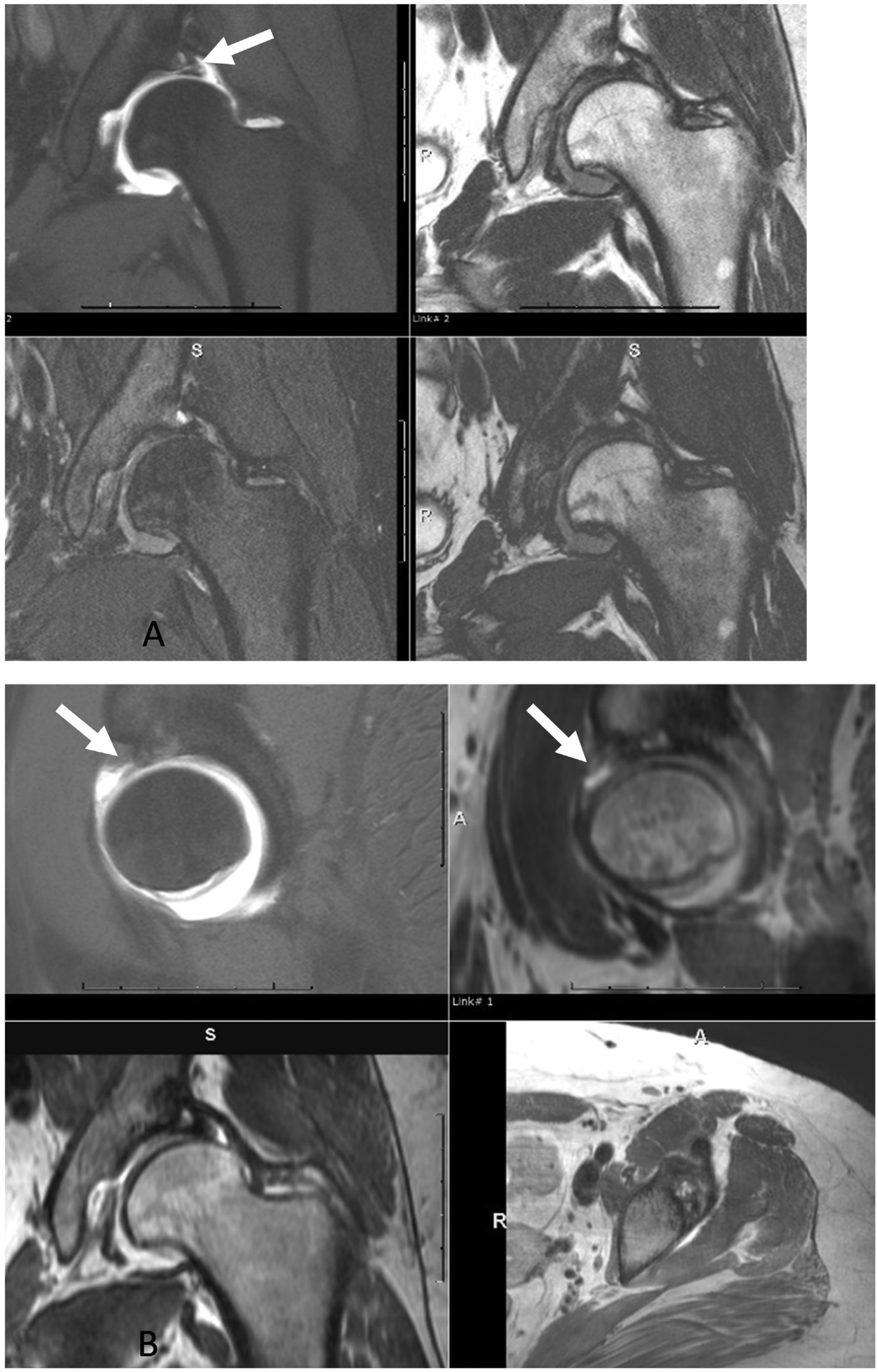

Figure 3 A 2D and 3D MR arthrogram of the same patient as in Figures 1 and 2. (A) Coronal fat suppressed T1-weighted (fsT1W) and T2 Dixon images (in-phase-IP, water-, and opposed-phase-OP) showing superolateral labral tear (arrow), subchondral cyst of acetabulum. (B) Sagittal fsT1W and 3D proton density fast spin echo multiplanar reconstructions show additional anterosuperior labral tear (arrows). (C) Coronal oblique 3D reconstruction allows measurement of the labral tear = 18.7 mm, outlined by the arrows. (D) Arthroscopy images before and after debridement of the large labral tear (arrows). (Color version of figure is available online.)

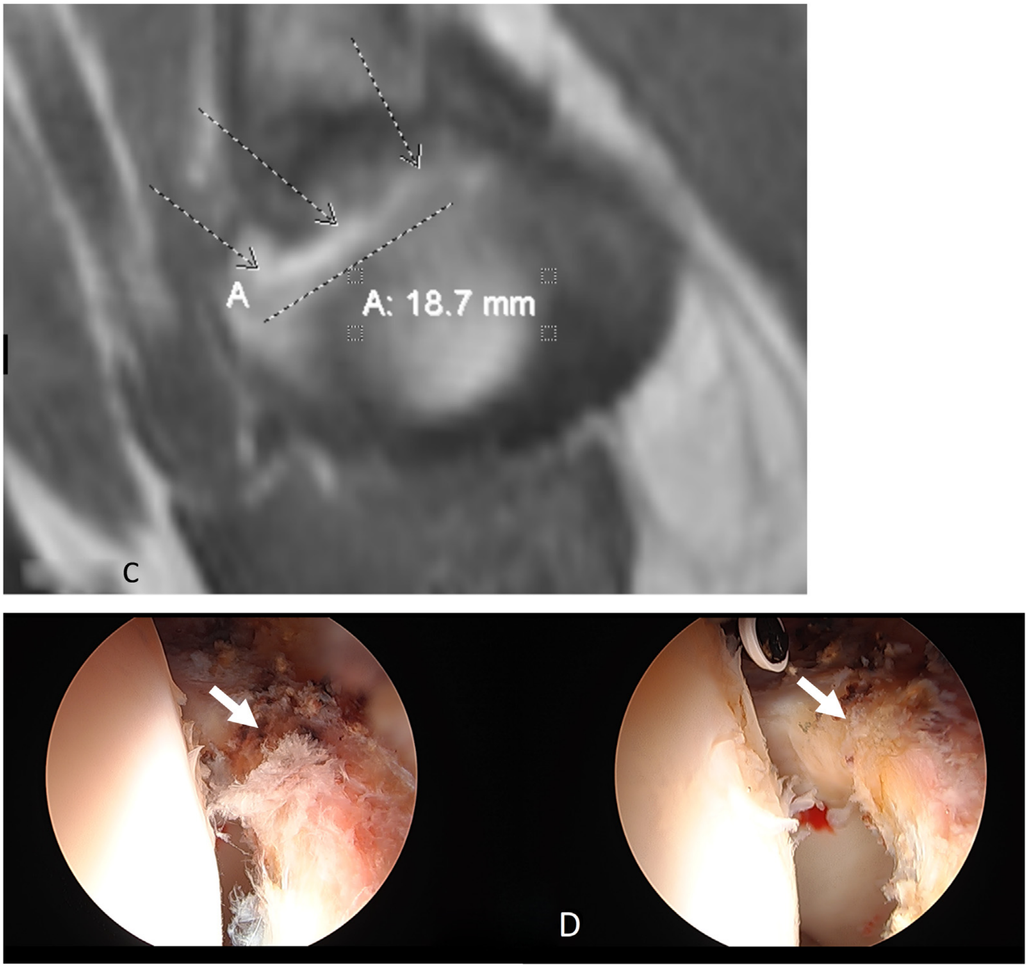

Figure 3 Continued.

In this article, we discuss the advantages and applications of 3D isotropic hip imaging (3D CT and 3D MRI) in surgical decision-making for common hip conditions, such as FAI, DDH, AVN, synovial lesions, and cartilaginous tumors.

Femoroacetabular Impingement Syndrome (FAI)

Background

FAI syndrome is a clinical manifestation of abnormal contact of femoral head and acetabulum due to a nonspherical head and/or misshapen, abnormally deep or malrotated acetabulum. Due to abnormal femoral and/or acetabular anatomy, labral and chondral pathologies arise through abnormal contact and forces across the hip joint.[9] FAI can be separated into 3 morphologies: cam, pincer, and mixed. In the cam-type morphology, the femoral head is aspherical due to abnormal bone formation along the anterolateral or inferolateral head-neck junction of the femur. This leads to flattening or convexity at the femoral head-neck junction, which causes impingement with the anterosuperior or superior acetabulum, especially during flexion and internal rotation. A pincer-type morphology results from the over coverage of the femoral head, commonly associated with acetabular retroversion. A mixed-type morphology has elements of both cam and pincer morphologies and is more frequently encountered than the isolated variants, especially with increasing age.[10]

Although clinical manifestations of FAI are well described in the literature, there is no consensus on the etiology of the syndrome. Based on the current research, the syndrome is most likely due to a variety of factors, such as excessive activity and genetics. For example, cam-type FAI is 2-8 times more prevalent in athletes participating in high-impact sports such as football, soccer, and hockey than in nonathletic controls.[11] One sibling study demonstrated that siblings of patients with a cam deformity had a relative risk of 2.8, while siblings of patients with a pincer deformity had a relative risk of 2.0.[12]

According to the 2016 Warwick Agreement consensus statement, which sought to clarify diagnostic and management criteria for the syndrome, the recommended diagnostic imaging includes an anteroposterior (AP) radiograph of the pelvis and a lateral femoral neck view of the symptomatic hip. In our hip preservation practice, Dunn, frog-leg lateral, and false profile views are also obtained in such patients, apart from regular AP weight-bearing pelvis view (standard 4-view series, Figs. 1 and 4). While AP view shows both hips for comparison, detects Tonnis grade (Table 1), suggests the

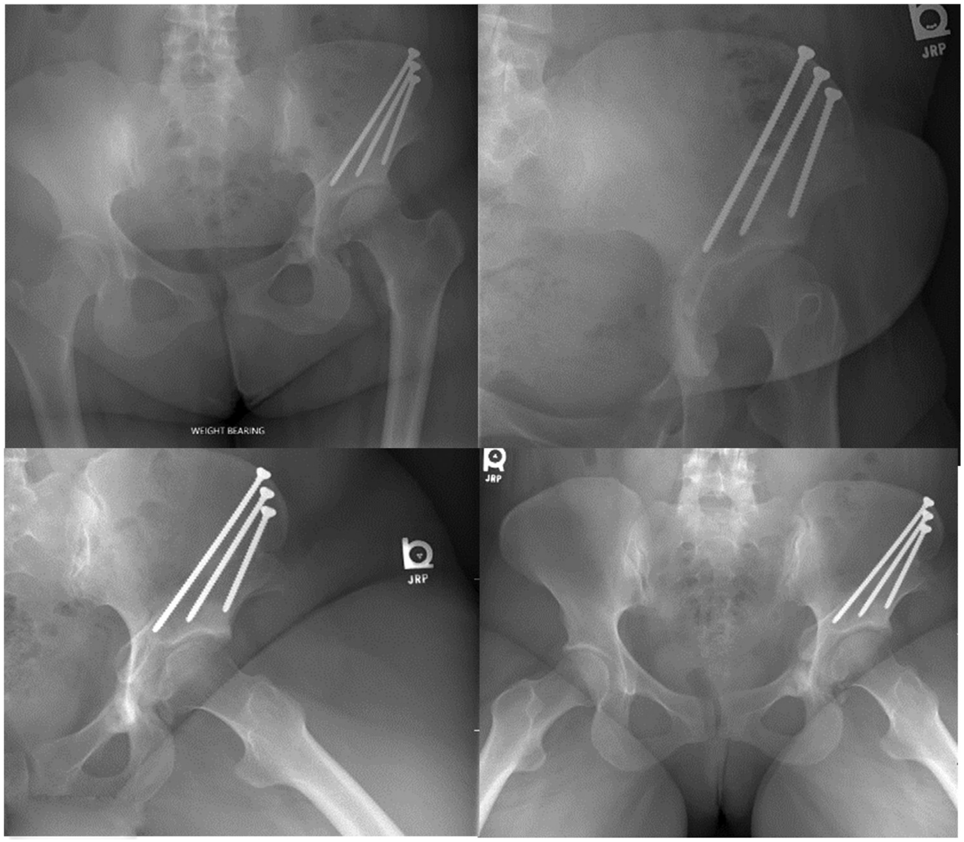

Figure 4 Postoperative 4-view radiographic series of the same patient following periacetabular osteotomy for correction of hip dysplasia. Notice adequate, near normal coverage of the left hip following the surgery.

degree of pelvic tilt, finds DDH and large bumps (at 12o'clock) of head and neck junction, and displays acetabular retroversion (figure-of-8 sign); individual views show bumps at different positions of femur (1-2o'clock in Dunn, 2-3o'clock in frog leg lateral, and anterior head over coverage on the false profile view). Other radiographic measurements commonly used for evaluating and diagnosing FAI are described in Table. 2 and Diagram 1, respectively.[13,14] Advanced imaging with CT and MRI are used to further assess the osseous anatomy, femoral version, soft tissue, and labral morphological changes (Fig. 5).[10] Advanced imaging measurements are crucial for preoperative planning and execution during surgery. Depending on the severity of the acetabular version, open procedures such as periacetabular osteotomy may be necessary over hip arthroscopy. Femoral torsion has been linked to worse outcomes after isolated hip arthroscopy and can further lead to lumbar spine pain and facet loading. Depending on femoral torsion measurements, derotational osteotomy may be necessary.[15-18] It has been shown that magnetic resonance arthrography (MRA) has higher sensitivity and specificity for the diagnosis of FAI syndrome when compared with conventional radiographic evaluation.[19]

Table 1 Tonnis Grading of hip Osteoarthritis Based on Radiographic Feature

Grade	Radiographic Features
0	No signs of osteoarthritis
1	Slight narrowing of joint space, slight lipping at joint margin, slight sclerosis of femoral head or acetabulum
2	Increased narrowing of joint space, small cysts in femoral head or acetabulum, moderate loss of sphericity of femoral head
3	Severe narrowing/obliteration of joint space, large cysts, severe deformity of femoral head, avascular necrosis

Table 2 Anterior-Posterior (A-P) Radiographic Considerations for Diagnosis of FAI

A-P Radiographic Characteristics for FAI	
Pincer Impingement	Cam Impingement
Lateral center edge angle $>39^\circ$	Pistol-grip deformity
Reduced extrusion index	Femoral Neck shaft angle (FNA) or Caput-
Acetabular index $\leq 0^\circ$	Collum-Diaphyseal (CCD) angle less than 125°
Coxa profunda	
Protrusio acetabuli	Horizontal growth plate sign
Focal acetabular retroversion	Alpha angle $>55^\circ$

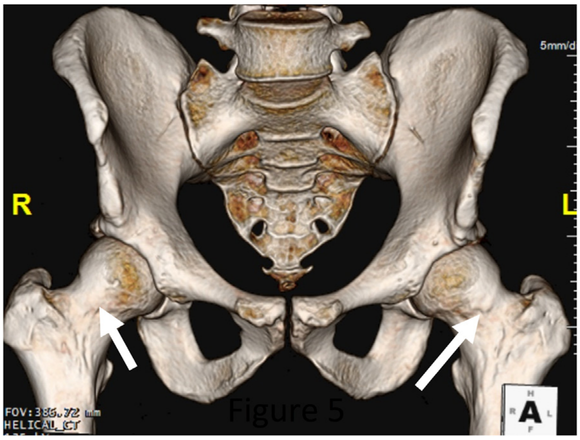

Figure 5 A 3D CT volume-rendered reconstructions of the pelvis and hips in an adult patient with bilateral femoroacetabular impingement (FAI). Notice large right and moderate head and neck bumps (arrows) (Color version of figure is available online.)

Surgical Management

Surgical management of FAI focuses on correcting the pathologic morphological changes and resulting soft tissue injuries, which consists of resecting the bony cause of impingement either arthroscopically or using an open technique.[20] Hip preservation is useful for Tonnis grade 2 or lower. Tonnis classification of hip osteoarthritis is a common staging system used and is displayed in the Table. 1 [21] For all practical purposes, anytime joint space is less than 2 mm, hip preservation surgery may fail or is contraindicated.

If a cam lesion is present that involves the femoral head-neck junction, a cam resection or femoral osteoplasty is performed to shave down the excess bone.[22] Removing the excess bone allows the patient an improved range of motion without pain and potentially slows soft tissue damage caused by the syndrome. The torn labrum is repaired or debrided depending on the severity of the injury with 2-4 sutures.[20] The cartilage lesions on acetabular side can be debrided and/or microfracture. Femoral sided chondral lesions, especially if large, may not be satisfactorily repaired and hip preservation may fail or is contraindicated in that setting.

Surgical intervention for FAI has seen a 6-fold increase from 2006 to 2010, but studies are inconclusive regarding which factors are the most important predictors of surgical outcomes.[23,24] A 2-year retrospective cohort study of 626 patients with FAI who underwent hip arthroscopy demonstrated that factors such as preoperative alpha angle, femoral chondral damage, and preoperative symptom duration are negative predictors for return to high activity sports.[25] Thus, there exists a need to determine the clinical and diagnostic criteria for when surgery is needed in FAI, and advanced imaging, that is, 3D CT and 3D MRI, has the potential to better guide surgical decisions by allowing superior assessment of cartilage and soft tissue damage.

Role of 3D CT and 3D MRI

The usage of 3D CT quantitative measurements has already been established in this domain[26] and has shown that pincer and cam morphology are frequent in asymptomatic subjects.[27] Resection surgery guided by 3D CT information has demonstrated improved bone resection accuracy versus conventional surgery and larger bumps are associated with larger labral tears.[28,29] 3D CT allows multiplanar isotropic reconstructions and measurements of femoral head and neck bumps at different positions of the femoral head and neck junction and acetabular and femoral torsional assessment.[30] Additional cut-out views above the acetabulum can demonstrate the acetabular coverage of the femoral head (Fig. 2). However, 3DCT involves radiation exposure and angular measurements and processing take excessive time currently.

Three-Dimensional MRI can demonstrate all the above lesions and allows measurements but does not confer an increased radiation exposure.[5] Thus, 3D MRI is preferred in younger patients. Another large study demonstrated that cam deformity and acetabular over coverage measured on pelvic 3D MRI evaluation are predictive of a symptomatic hip state.[31] Thus, 3D MRI can be used as a tool to screen patients preoperatively and guide surgical interventions. The specific advantages of 3D MRI include- isotropic sub-1.0 mm evaluation of labrum and cartilage, measurement of labral lesions along the axis of the labral tear, superior identification of full-thickness extent of labrum tear or cartilage loss, finding subchondral fractures with osteochondral injury, and conspicuous appearance of perilabral cysts and subchondral cysts. Osseous advantages include radial imaging of femur or acetabulum without the need for additional image acquisition, and measurements of alpha angle and acetabular version. Finally, postoperative assessment is facilitated with 3D MRI, and MR arthrogram can be avoided to detect labral re-tears, residual bumps, wide/persistent postoperative capsular defects, and chondral damage due to superior fluid contrast of 3D imaging (Figs. 6 and 7).

Developmental Dysplasia of the Hip (DDH)

Background

DDH stems from improper development of the acetabulum due to femoral head subluxation or dislocation leading to persistent inadequate coverage of the femoral head. If left untreated, it can result in premature osteoarthritis, hyaline cartilage damage, and labral tears.[32] Early identification of the condition can be achieved through routine evaluation of the infant's hip through the Barlow and Ortolani physical examination maneuvers. The Barlow maneuver consists of adducting the hip to the midline and gently applying posterior force. If the femoral head subluxes, a clunk is felt and the test is considered positive, which indicates that the femoral head is resting in the acetabulum but is unstable. The Ortolani maneuver is performed while the thighs are adducted and posteriorly depressed, and the hips are abducted while applying anterior

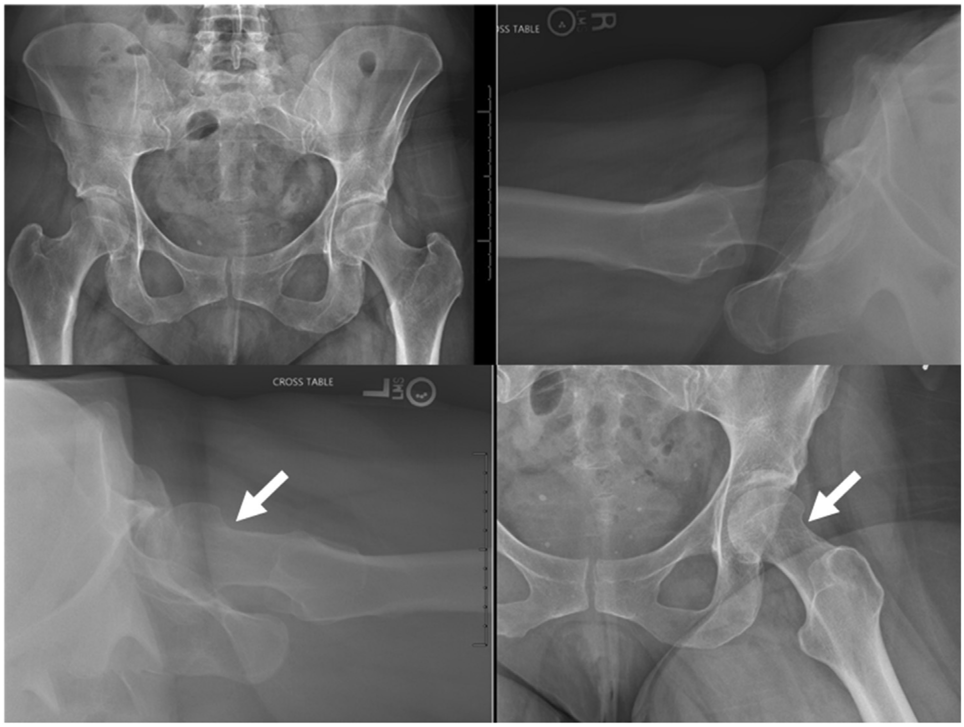

Figure 6 A 54-year-old man with known left hip FAI and prior surgery with bump resection and labral repair presenting with persistent pain. Notice cam plasty changes (arrows).

pressure at the greater trochanters. A clunk will be felt if the femoral head relocates, and the test is again considered positive. A hip that tested positive on the Ortolani test is dislocated at rest, therefore, considered more severe than a Barlow-positive hip.[33] The etiology of the condition is not well established, but there are a number of risk factors identified, such as breech positioning in utero, female sex, being firstborn, and positive family history.[34]

Ultrasound is the recommended imaging modality in infants under 4 months old since the infant's hip is mostly cartilaginous, making radiographic visualization difficult or impossible. However, once femoral head ossification begins at around 4-6 months of life, radiographs become the preferred method of evaluating and monitoring DDH. Tonnis angle of more than 10 degrees and lateral center edge angle of less than 20 degrees on AP pelvis view are used as diagnostic markers of DDH (20-25 degrees being considered borderline DDH). A commonly used staging system to determine the severity of hip dysplasia is Crowe's Classification, outlined in Table 2.[35] There is a higher predisposition of transitional lumbosacral anatomy in DDH patients, but it has not been shown to affect their functional outcomes.[36,37] MRI is used to detect intra-articular pathology and better characterize patients' hip morphology.[38]

Surgical Management

Treatment efforts in DDH focus on keeping the femoral head in the acetabulum so that the femoral head is stimulated to grow normally. By increasing the femoral head coverage, the orientation of the weight-bearing zone is optimized, and it can lead to reduced joint contact pressure and decreased risk for osteoarthritis and soft tissue damage.[39] Three main principles guide the treatment plan: to concentrically place the hip, take serial radiographs of the hip as the child grows to confirm sustained correction of the acetabular dysplasia, and perform pelvic or femoral osteotomies if there is residual dysplasia or the initial hip reduction is not enough to correct the acetabular dysplasia.[33] Periacetabular osteotomy is used in recalcitrant cases with lower Tonnis grades (Figs. 1-4). Additional femoral derotational osteotomies to correct excessive antetorsion or femoral head and neck bump resections can be performed for inferolateral bumps (not uncommon in long-standing DDH cases). The underlying cartilage and labral damage are repaired. In higher Tonnis grades of osteoarthrosis, hip preservation may be contraindicated, and hip resurfacing or total hip arthroplasty is performed.

Role of 3D CT and 3D MRI

3D CT scans have been shown to improve surgical results when used for pre-surgical planning to visualize femoral and acetabular anatomy, similar to FAI syndrome as discussed earlier.[5] However, CT scans can deliver excessive radiation in young patients, especially those of childbearing age, since the CT radiation dose to the pelvis is approximately 5mSv to 7mSv per exam.[40] On the 3D volume rendered images, the femoral head lateral extrusion (more than 18%) and acetabular under coverages are nicely demonstrated. On the cut-out view, one can show the anterior, posterior, or global under coverage by the acetabulum (Fig. 2). The angular

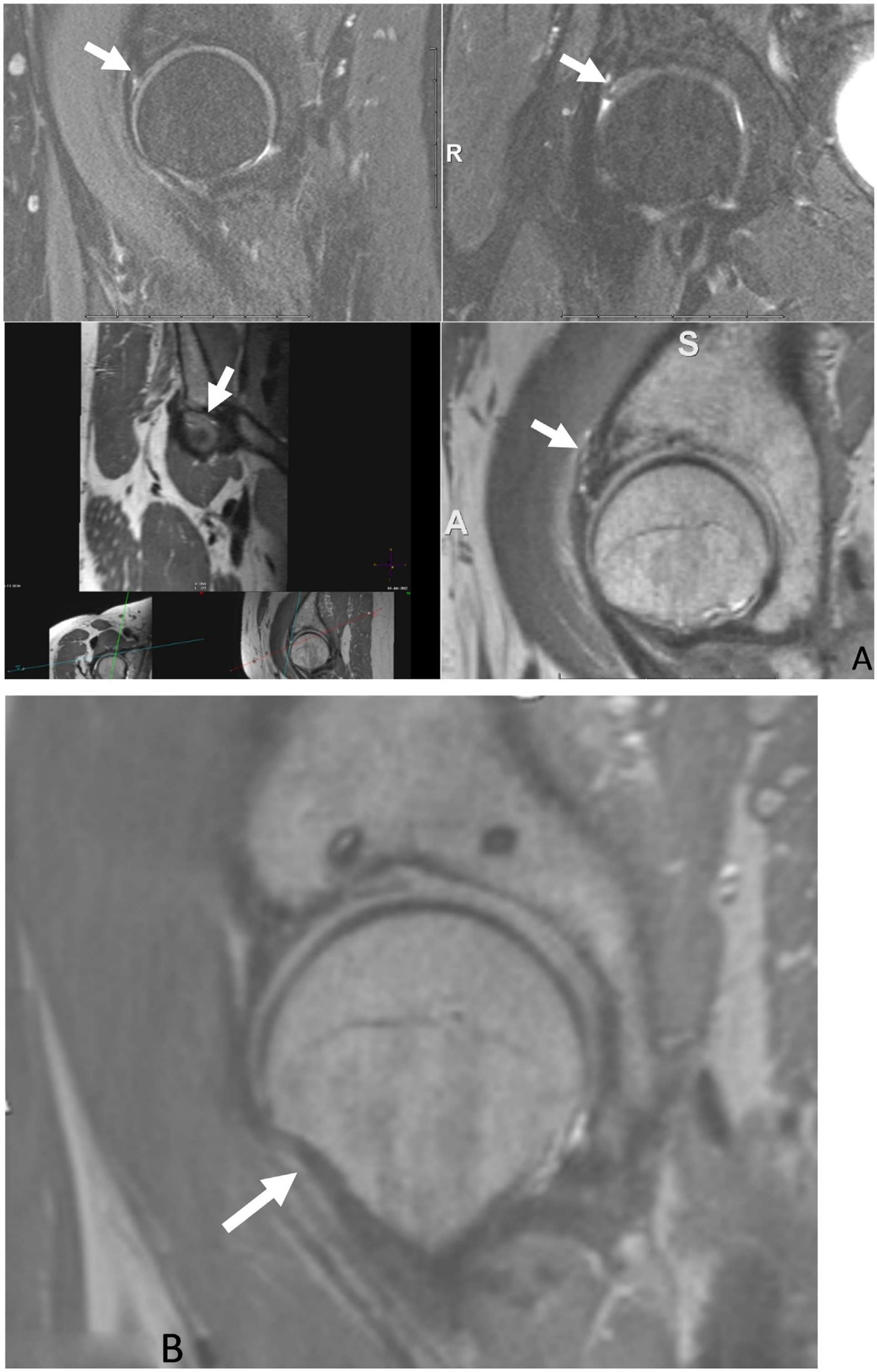

Figure 7 (A). MRI of the same patient as in Figure 6. Two-dimensional MRI (top panel) shows anterosuperior and superolateral labral re-tear (arrows). Three-dimensional MRI (bottom panel) again allows evaluation of the extent of the labral tear and also shows the superior extension of the paralabral cyst (arrows). (B) Three-dimensional sagittal image shows the labral sutures of the acetabulum (arrow) and cam plasty changes.

measurements are also obtained to demonstrate increasing alpha angles at 2-3 o'clock, an inferolateral bump in DDH as compared to 1-2 o'clock bump of FAI. Three-Dimensional radial imaging reconstructions and assessment of sector angles can be obtained by both 3D CT and 3D MRI without partial volume artifacts. Three-Dimensional MRI also offers similar imaging advantages as 3D CT scans and does not expose the patient to unnecessary radiation.

Avascular Necrosis (AVN)

Background

Osteonecrosis or avascular necrosis (AVN) of the hip arises from an insufficient vascular supply to the femoral head. Often idiopathic in origin, its occurrence is most observed within the 20- to 40-year-old age group.[41] The femoral head is predisposed to developing avascular necrosis due to the limited blood supply between cranial and caudal supply regions of the obturator and circumflex arteries, respectively. The watershed zone is primarily supplied by the foveolar artery (from the obturator) and is often implicated in the development of this pathology. The predisposing factors include traumatic events, such as femoral head or neck fractures, dislocations, and slipped capital femoral epiphysis. Additionally, atraumatic factors, such as chronic glucocorticoid use (35%-40% of cases) and alcohol use disorder (20%-40%) are amongst common etiologies precipitating these lesions. These lesions are initially screened using radiographs and staged according to their imaging appearances (Table 3). Further evaluation is performed utilizing MRI (Table 4).

On T1-W (weighted) images, AVN classically presents with a crescentic band of low signal in the subchondral femoral head bone marrow. This band is thought to represent the interface between the necrotic and reparative zones. On T2 weighted and inversion recovery sequences, subacute AVN classically shows 2 serpentine lines: an inner bright line representing reparative granulation tissue and an outer dark line representing adjacent sclerotic bone. The outer line is always continuous, while the inner line can be discontinuous or absent. Dixon imaging allows multiple maps, and AVN margins and subtle femoral head collapse are best defined on opposed-phase imaging, while edema of activity is best seen on water images (Fig. 8)

Table 3 Crowe's Classification of hip Dysplasia

Group	Description
I	Subluxation is <50% or proximal dislocation is <0.1% of pelvic height
II	Subluxation is 50% to 75% or proximal dislocation is 0.1% to 0.15% of pelvic height
III	Subluxation is 75%-100% or proximal dislocation is 0.15% to 0.2% of pelvic height
IV	Subluxation is >100% or proximal dislocation is >0.2% of pelvic height

Surgical management

Stage 1 or 2 AVN without subchondral collapse or secondary osteoarthritis often presents in young patients with age range of 24-45 years. It is often idiopathic or corticosteroid-induced.[42] For this population, core decompression, osteotomy in consideration for bone grafting, and vascularized fibular grafting are preferred treatment options that can relieve symptoms. Whereas in an older population with higher AVN staging, hemi- or total hip arthroplasty are the viable options. Intraoperatively, AVN can be further complicated by excessive bleeding due to acute and chronic inflammatory changes that produce a hyperemic capsule and synovitis. It is not uncommon to additionally find a large synovial effusion that increases the risk for sepsis. Therefore, advanced imaging is used preoperatively to clearly demonstrate the location, depth, and stage of AVN for intraoperative management and distinguish it from other causes of epiphyseal lesions such as chondroblastoma, histiocytosis, and subchondral cysts.

Role of 3D CT and 3D MRI

3D CT is useful for delineating AVN extent, but its primary value lies in showing under or over-coverage of femoral head with lateral column involvement by AVN, or subtle subchondral collapse or fracture (crescent sign). The lateral column involvement can increase susceptibility of collapse, i.e. FICAT stage III similar to the Perthes disease. Three-Dimensional MRI can show small geographic lesions of AVN, early

Table 4 FICAT and ARLET Classification of Osteonecrosis

	Clinical Features	Radiograph	MRI	Bone Scan
Stage 0	None	Normal	Normal	Normal
Stage 1	Pain in groin	Minor Osteopenia	Local Edema	Increased uptake
Stage 2	Pain and stiffness of affected hip	The following findings may be present: -Osteopenia -Sclerosis -Crescent Sign	Geographic defect in the affected hip	Increased uptake
Stage 3	Pain and stiffness of affected hip with possible radiation to knee. Patient may also present with gait abnormalities	The following findings may be present: -Crescent Sign of a subchondral fracture -Cortical collapse	The following findings may be present: -Crescent Sign of a subchondral fracture -Cortical collapse	
Stage 4	Extreme pain and stiffness of affected hip with gait abnormalities.	-Collapse with flattening of femoral head -Decreased joint space	-Collapse with flattening of femoral head -Decreased joint space	

Figure 8 (A). Fifty-four year-old man with bilateral avascular necrosis of the femoral heads (FICAT stage II on radiographs). (B). IP and water images of T2-Dixon sequence confirm the AVN bilaterally. (C). MRI shows extensive necrosis of the femoral heads. (C and D): IP, OP, water axial images show the full extent of the lesions and bone marrow edema of the femora neck suggesting ongoing activity on the right side. In addition, notice subtle anterosuperior head collapse on sagittal OP image (arrow) consistent with FICAT stage III AVN on MRI.

subchondral fracture (that upstages the lesion) or subchondral collapse, and associated large chondral lesions, which may preclude core decompression or further hip preservation. Three-Dimensional postcontrast T1W and 3D perfusion imaging allow assessment of viable tissue around the infarct and associated hip synovitis (Figs. 9 and 10), while diffusion weighted imaging allows evaluation of enhanced bone diffusion in the viable areas around the geographic infarct (Fig. 11).

Hip Fractures and Cartilage Loss

Background

In continuation from the previous section, the development of AVN predisposes patients to cartilage loss and fractures, which need to be appropriately screened throughout the patient's disease state. Identification of early cartilage degeneration or osteochondral lesions from trauma is important to monitor progression and provide treatment in a timely manner. Hip fractures can occur from a variety of etiologies, most commonly motor vehicle trauma. The patients often present with multiple injuries and may have subluxation/dislocation of the joint and fractures that require in-patient management of care. Non-displaced fractures can be particularly difficult to diagnose on radiographs and can be challenging on CT as well. These lesions can be more obscure in the elderly population due to bone demineralization. Thus, MRI is very helpful in screening for these injuries and evaluating associated soft tissue injuries, such as tendon tears. Expeditious treatment or immobilization can prevent premature cartilage damage and rapid progression of osteoarthrosis.

Surgical Management

Initial treatment for most hip dislocations and fractures is to attempt a closed reduction and percutaneous fixation with dynamic hip screws if non-displaced or minimally displaced

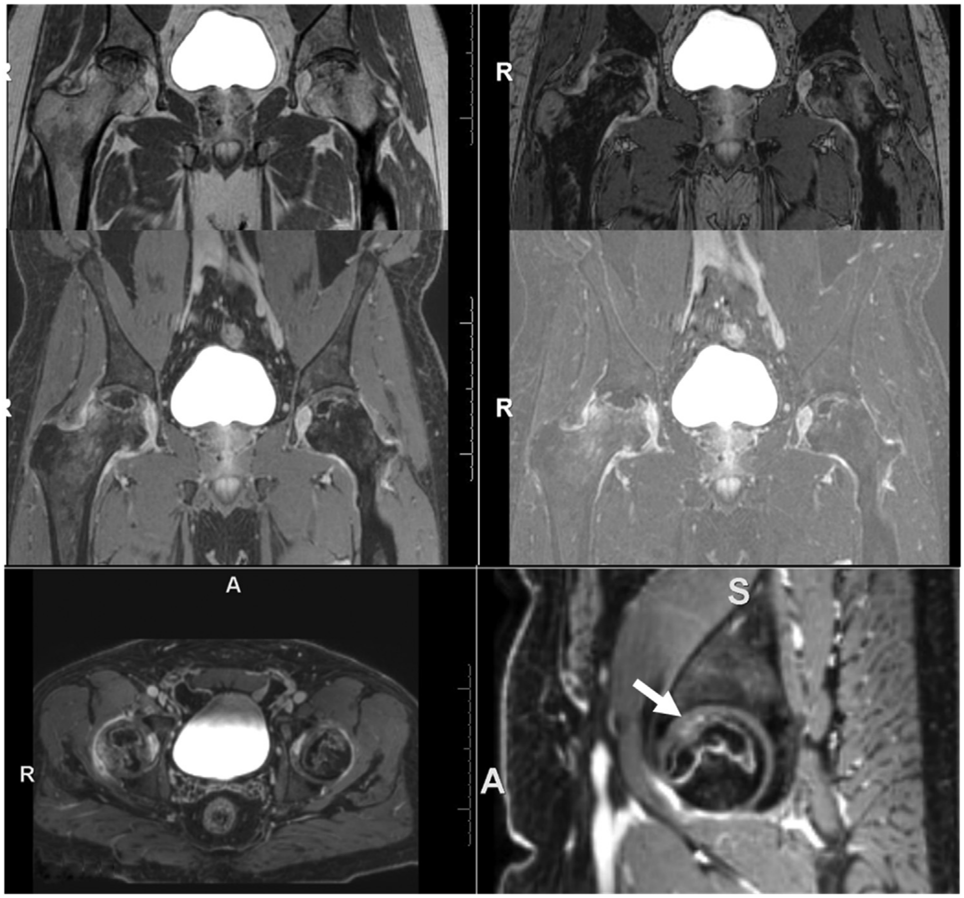

Figure 9 Postcontrast delayed enhanced MRI of the same patient as in Figure 8 using T1-Dixon images shows bilateral hip synovitis and cortical enhancement at the collapse site of anterosuperior femoral head on the sagittal image (arrow) confirming FICAT stage III AVN.

femoral neck fractures are identified on imaging. There continues to be a debate on the predisposing pathologies that can complicate post-operative care, such as arthritis or the need for hip replacement at a later date. Evidence has shown that associated cartilage damage places a larger post-operative rehabilitation burden on the patient.[43] Therefore, some surgeons may choose to perform a hip arthroplasty if there is a significant coexistent cartilage loss or damage. Osteochondral injuries can be addressed by arthroscopy and microfracture/allografts, especially in young patients.

Role of 3D CT and 3D MRI

Three-Dimensional CT shows femoral and acetabular fractures in superior detail for presurgical planning, especially in the setting of dislocation. Bone density assessments can be made at the fracture sites for the diagnosis of osteoporosis. Volume rendered and maximum intensity projections in anatomic planes of hip and femur are particularly helpful in identifying these fractures and displaying them elegantly for presurgical planning. Dual energy CT bone marrow maps can show bone marrow edema at the site of fractures leading to their timely detection and can increase the confidence of a radiologist for accurate interpretations. Three-Dimensional MRI helps find small osteochondral injuries, ligamentum teres tears, and otherwise inconspicuous fracture lines in the cloud of bone marrow edema, thus differentiating them from a geographic zone of AVNs. Additional benefits include high resolution depiction of associated subtle labral, capsular, tendon, and cartilage injuries.

Synovial Lesions

Background

Synovial lesions can significantly impact a patient's quality of life. These lesions present clinically with swelling, pain, and restriction of motion of the affected joint. Therefore, establishing an accurate diagnosis is vital to provide patients with appropriate care and assistance to maintain a high quality of life. The most common cause of synovial hypertrophy is osteoarthrosis, while other common causes include synovial chondromatosis, villonodular synovitis, and lipoma arborescens.

When the synovial tissue undergoes proliferation and subsequent metaplasia into cartilaginous or osteocartilaginous tissue, the phenomenon is termed synovial chondromatosis (SC) or osteochondromatosis, respectively.[44] The early stage presents with chondrometaplasia without the presence of loose bodies, followed by a transitional stage with loose

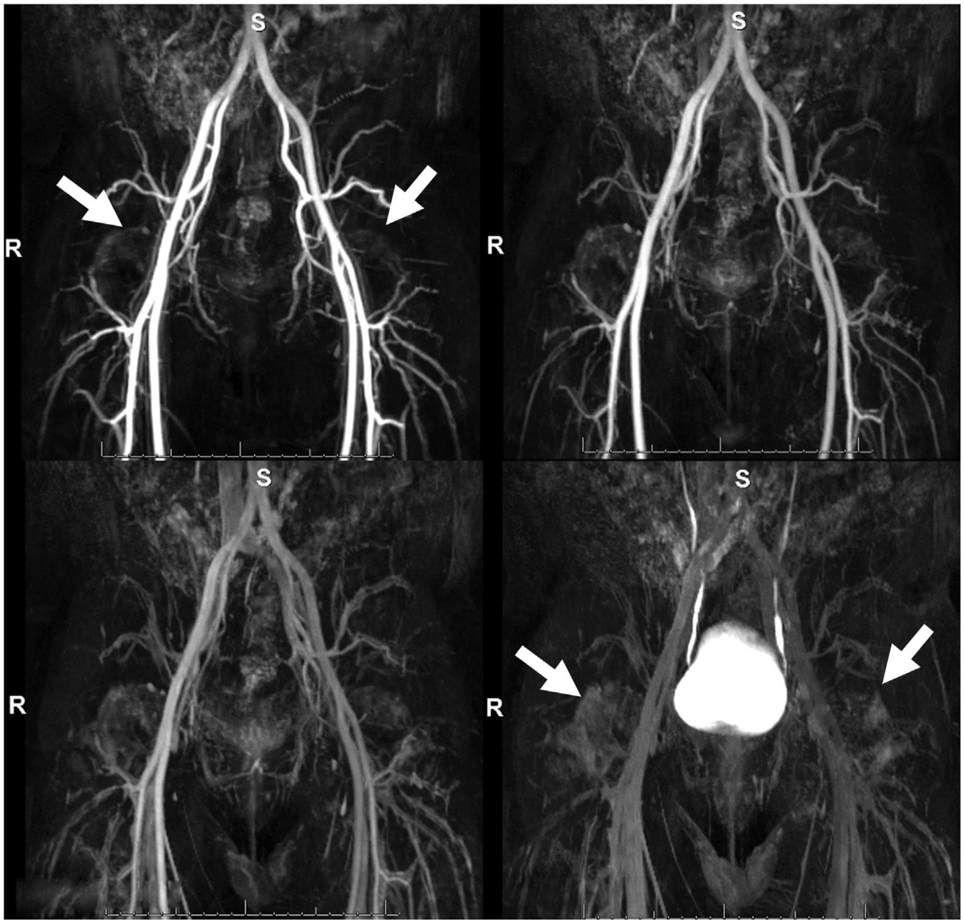

Figure 10 Sequential MR perfusion images of the same patient as in Figures 8 and 9 show focal avascular areas of AVN with peripheral progressively increasing perfusion and synovial enhancement bilaterally.

bodies alongside active disease and finally, a late stage with loose bodies without active disease. Histologically, nodules of hyaline cartilage are observed with clustered chondrocytes which may or may not be binucleated. Two-Dimensional MRI is limited to visualizing a baggy or capacious capsule with increased effusion indirectly hinting at the presence of SC. On 3D MRI, due to the higher resolution, individual loose bodies can be seen, which tend to be numerous and of similar sizes in primary SC and countable (fewer) with different sizes in secondary SC. Plain films may show calcifications, helping differentiation of SC from the below described entity of pigmented villonodular synovitis.

Pigmented Villonodular synovitis (PVNS), aka giant cell tumor of the tendon sheath, produces a nodular synovial mass in the localized variety versus multifocal lesions in the diffuse variety. Histologically, giant cells, histiocytes (foam cells), hemosiderin deposition and fibrous tissue are seen within the lesion. PVNS can be seen in the intraarticular

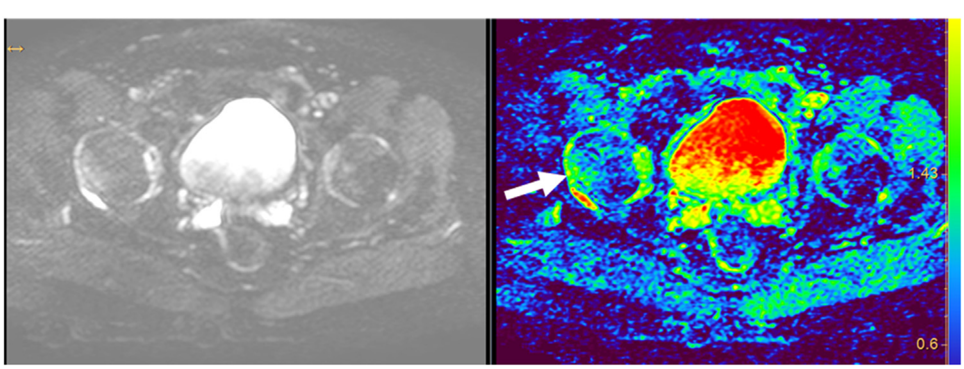

Figure 11 Diffusion-weighted imaging shows peripheral edema and T2-shine through effects with increased ADC (in green; arrow) suggesting presence of viable bone around the area of infarct (Color version of figure is available online.)

location or extra-articular peri-tendinous location. This condition most commonly presents in adults as a painless, enlarging mass.[45,46] The knee joint is most commonly affected, however, other joints such as hip, ankle, wrist, shoulder can be affected as well (Fig. 12 and 13). The hypertrophied villonodular synovium can result in eccentric cortical erosions. On MRI, one can see an intermediate signal intensity mass, which may produce susceptibility artifacts on T2W gradient echo imaging or increased signal on opposed phase Dixon imaging as compared to the in-phase due to presence of hemosiderin (Fig. 12). The enhancement is variable but usually shows early and persistently intense uptake on 3D perfusion gadolinium imaging (Fig. 12). Calcifications are absent as compared to related differential diagnosis of SC. In addition, PVNS is darker on ADC while SC is brighter without significant restriction of proton diffusion.

Another synovial hypertrophic condition characterized by lipoma like fibrofatty proliferation of the synovium is known

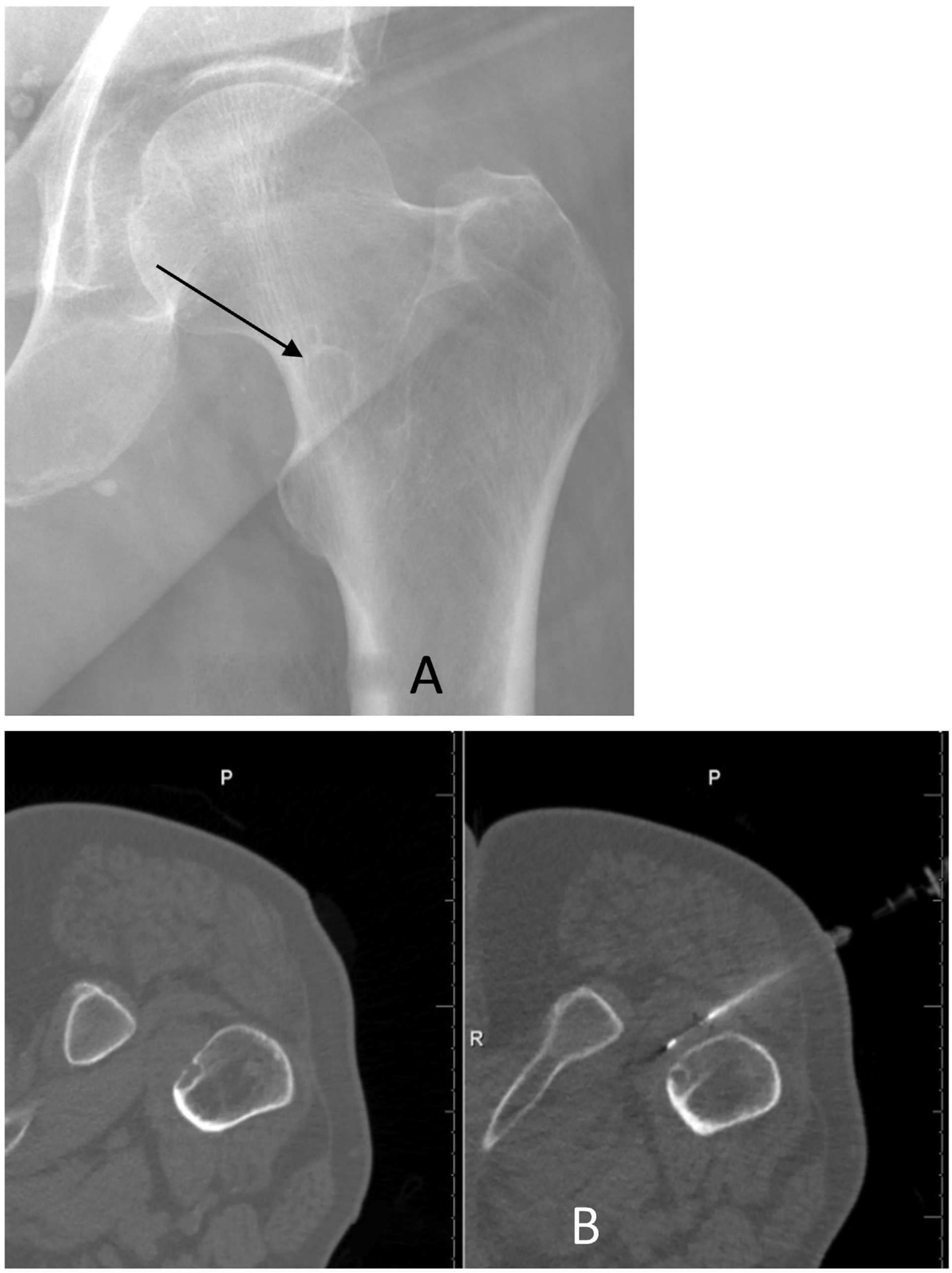

Figure 12 (A). AP radiograph of 59-year-old man with pigmented villonodular synovitis (PVNS) and enchondroma of the left femur. Arrow points to a well-defined radiolucent lesion with peripheral sclerosis. (B). Axial CT images obtained during percutaneous biopsy with confirmation of PVNS. (C). T2 Dixon and (D). Postcontrast fsT1W, perfusion, and subtraction images showing typical imaging findings of PVNS/tenosynovial giant cell tumor, that is, increased signal on OP images, eccentric cortical erosion, early and persistent perfusion, and intense enhancement (solid arrows); and of enchondroma (popcorn like T2 bright lesion, some loss of signal on OP images and peripheral enhancement (thin arrows).

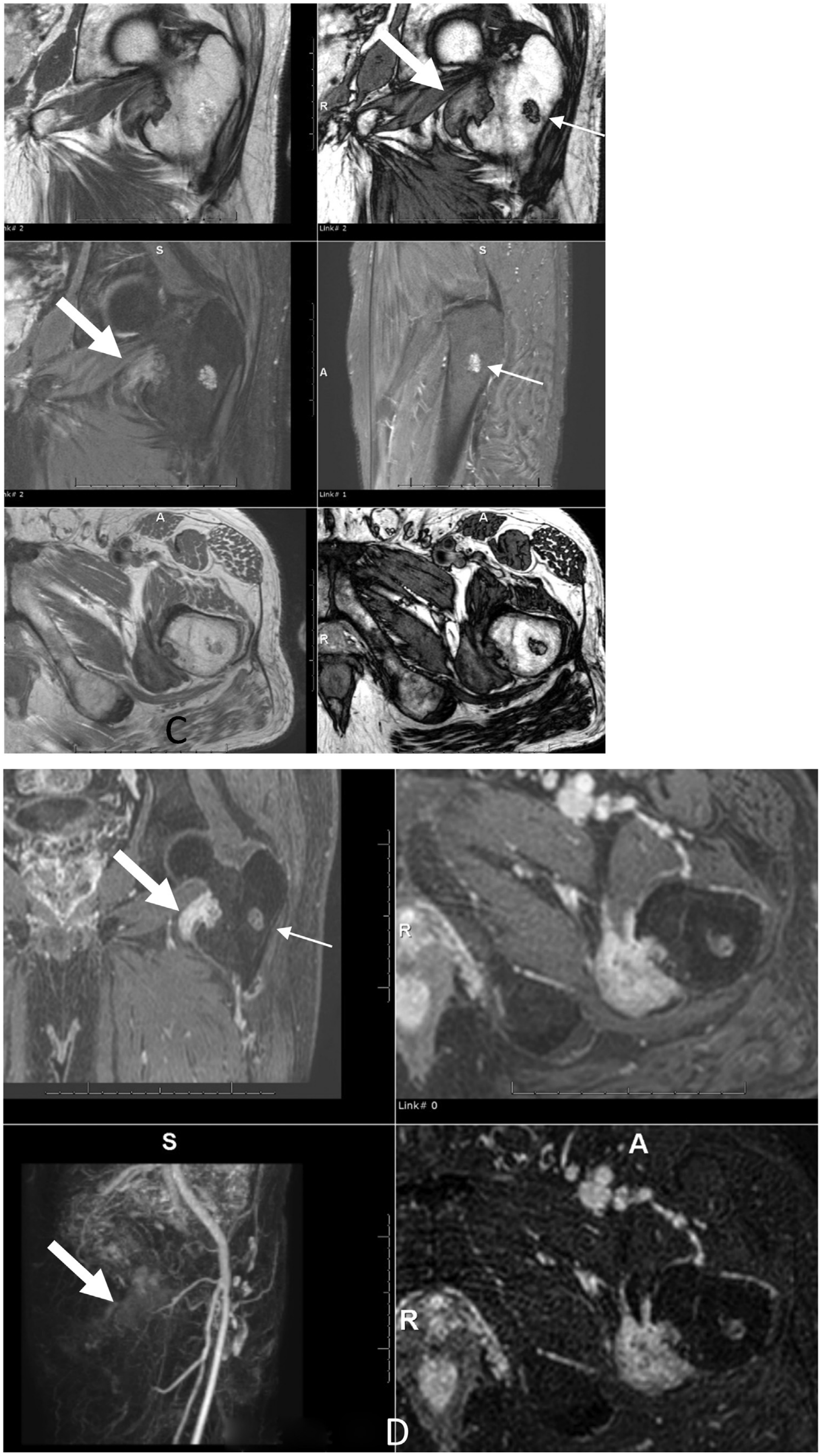

Figure 12 Continued.

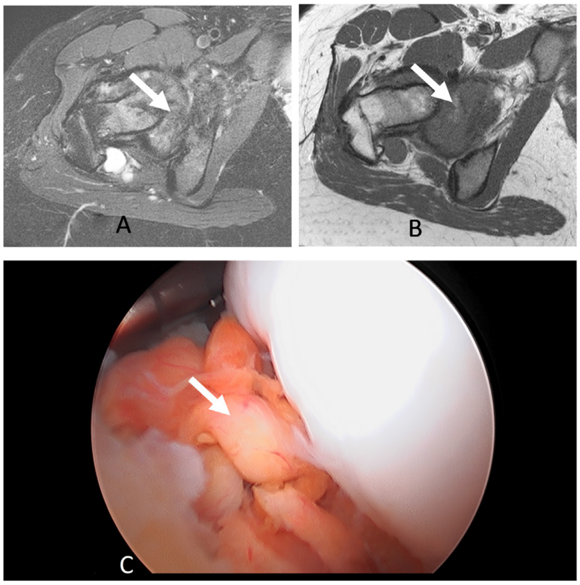

Figure 13 (A). Axial water image and (B). IP image show diffuse nodular synovial mass of the right hip in keeping with PVNS (arrows). (C). Arthroscopic confirmation of the final diagnosis of PVNS/tenosynovial giant cell tumor (arrows) (Color version of figure is available online.)

as lipoma arborescence. On imaging, it presents as diffuse villous proliferation of the synovium, which may be small and feathery or in the form of bulky fat lobules. This most commonly affects the knee but can also be seen in the hip or shoulder as a primary variety or secondary to long-standing inflammatory arthropathy.

Surgical Management

There are variations in the surgical treatment of synovial disorders, but the cornerstone is the removal of the pathology as much as possible, if symptomatic, to reduce pain and improve the range of motion of the joint. Synovial chondromatosis and focal PVNS require either an arthroscopic or open synovectomy.[47,48] Furthermore, giant cell tumor, especially diffuse variety, has the propensity to return and must be completely excised. If the surgery fails to contain pathology, radiotherapy can be considered. Due to the extent of the joint affected, further degenerative changes of the joint are not uncommon and, thus, may require an arthroplasty in the longer term to manage the sequelae of symptoms.[49]

Osteo-cartilaginous Neoplasms

Background

Osteosarcoma is a tumor of malignant osteoid cells. It is the most common nonhematologic malignant bone tumor and accounts for approximately 20% of this subclass of malignancies.[50] It can be present in individuals of all ages and is seen most commonly during the first and second decades of life.[51,52] Osteosarcomas are further characterized as either primary or secondary osteosarcomas, where primary osteosarcomas occur in healthy bone, secondary osteosarcomas occur in a bone that is affected by a preexistent pathology such as Paget's disease, chronic osteomyelitis, or an area of bone with significant radiation exposure.[45,53,54] Furthermore, radiation associated osteosarcomas are more likely found in the skull, spine, scapula, pelvis, and clavicle.[55] The tumor often presents with unique, poorly defined ossified characteristics that allow it to be identified on plain radiographic imaging. "Hair-on-end" or "sun-burst" appearance of periostitis and periosteal elevation (Codman's triangle) are typical findings.[56,57]

Chondrosarcoma is the next most common nonhematologic malignancy of bone, constituting approximately 9% of malignant, primary bone tumors.[58] It can occur in nearly any age range but usually peaks between the ages of 40-60 for primary chondrosarcoma and 25-45 for secondary chondrosarcoma.[59] They most commonly occur at a proximal location in the body, such as the pelvis, proximal femur, or proximal humerus.[60,61] Rarely do they occur in hand, but they are the most common malignant bone lesions at this location.[62,63] These tumors consist of mesenchymal cartilage producing cells and are histologically nearly identical to enchondromas due to the degree of cartilage tissue in the specimen. Therefore, findings of hypercellularity, binucleate cells, entrapped bony trabeculae and a permeating pattern can influence differentiating between benign and malignant processes. Tumor location and invasion are additional clues that can support diagnosis.[56,64] For example, a solitary chondroid tumor of pelvis is more likely to be a chondrosarcoma than one of the same histology found in hand, periosteum, long-bone, or synovium.[56,65] Clear cell chondrosarcoma occurs in the epiphysis of bone, most significantly in the proximal femur. They are named according to what is observed on histology-large, clear cells with distinct borders and multi-nucleated giant cells surrounded by a cartilaginous matrix. Clear cell chondrosarcomas are a low-grade malignancy and thus can have benign radiographic features.[66] As imaging is more likely to reveal a benign mass, it is challenging to diagnose with imaging alone as it does not have characteristic defining features.[66,67]

Treatment

Patients with high-grade osteosarcoma undergo immediate radical or wide amputation with neoadjuvant chemotherapy to treat subclinical micro metastases that can present at a later date.[52,68] Furthermore, histological response of the primary tumor to neoadjuvant chemotherapy is used for estimating treatment success.[69,70] High-grade osteosarcomas are challenging to treat as most patients show some degree of relapse after treatment; approximately 10% of patients can have a local recurrence after removal and are associated with poor outcomes and require additional surgery and chemotherapy.[71,72] Low-grade osteosarcomas are primarily treated surgically without the need for chemotherapy.

Treatment for chondrosarcomas continues to be debated, as they are generally resistant to chemotherapy and radiation. However, physicians have found successful results via extended curettage with additional intralesional treatments such as irrigation with cytotoxic agents and cryotherapy.[73,74] Due to difficulties in determining the potential malignancy of the tumor, it can be challenging to predict tumor recurrence. Definitive high-grade chondrosarcomas and indeterminate tumors with soft tissue invasion are treated aggressively with a wide or radical resection or amputation.[75,76] Lesions in an expandable location are also aggressively treated with primary wide resection without biopsy to reduce the risk of tumor contamination. Recurrence rates after wide resection have shown to be less than 10%.[77] Caution is advised during surgical planning, as tumors that are not completely resected are likely to recur. Long-term follow up with regular intervals of imaging of the operative site is done to monitor for tumor recurrence, assess for tumor growth and plan for surgical removal when identified.

Role of 3D CT and 3D MRI for Bone Tumors

Three-Dimensional MRI can be used for morphological mapping and anatomic localization of benign bone tumors and malignancies. Isotropic 3D MRI provides significantly improved out-of-plane resolution than traditional 2D MRI, which can mitigate volume averaging artifacts and allow for reconstructions in any plane with very thin image slice thickness from a single high-resolution isotropic acquisition. This is helpful in the assessment of tumors, surrounding nerves and vasculature, as well as bone shape analysis.[6] Three-Dimensional postcontrast T1W imaging and subtraction are useful on higher field scanners for producing multiplanar reconstructions from a single acquisition.

In CT, 3D multiplanar reformat imaging can be particularly valuable in delineating the nature of osseous involvement by the lesions and their extent for preoperative planning and for 3D printing of metal hardware. Furthermore, 3D reconstructions can help map out vasculature to aid the surgeon in ensuring that a comprehensive and safe surgical approach is achieved. Three-Dimensional rendering can also serve as a tool for patient and trainee education, as it helps in showing the lesion extent as well as the surgical approach.

Conclusion

The need for clear and high-resolution imaging that supports physician decision-making cannot be understated. Three-Dimensional isotropic spin-echo type MRI has a significant potential to positively influence surgical outcomes by building upon the knowledge achieved from current 2D MRIs. Due to advancements in technology and software, obtaining excellent 3D imaging of the joint in less than 5 minutes of acquisition is possible, thereby avoiding the need for an MR arthrogram. This technology can now be realistically incorporated into current hip preservation practices to improve such patients' clinical decision-making and surgical outcomes.

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