Skeletal Radiology (2021) 50:381–388
https://doi.org/10.1007/s00256-020-03566-x

SCIENTIFIC ARTICLE

Comparison of 2D, 3D, and radially reformatted MR images in the detection of labral tears and acetabular cartilage injury in young patients

Stephanie Watson Mayer[1,2] · Anne Skelton[1] · Jonathan Flug[3] · Tatum McArthur[3] · Whitney Hovater[1] · Patrick Carry[1] · Michael Fadell[1,3]

Received: 21 May 2020 / Revised: 24 July 2020 / Accepted: 27 July 2020 / Published online: 8 August 2020

Abstract

Objective The purpose of this study was to compare the utility of two-dimensional high-resolution (2D), 3-dimensional with multiplanar reconstruction (3D MPR), and radially reformatted (RR) MRIs when evaluating the complexities of the hip joint in patients with femoroacetabular impingement (FAI). We hypothesized RR would be superior in detecting labral pathology and 2D would be superior in detecting transition zone and acetabular cartilage injury.

Materials and methods 2D, 3D MPR, and RR MRIs of 33 patients, who later underwent surgical treatment for FAI, were evaluated for sensitivity, specificity, and accuracy. Bland-Altman methods were used to estimate agreement between each method and the gold-standard, arthroscopic visualization of the hip joint, regarding the percentage of the hip joint affected by each injury type.

Results 3D MPR and RR groupings were associated with the highest sensitivity and accuracy for labral injury. 3D MPR demonstrated the smallest bias in assessing the percentage of joint affected by labral injury and was the most accurate in identifying acetabular cartilage injury, whereas RR had the smallest mean difference in assessing the percentage of joint affected by acetabular cartilage injury. 2D was the most accurate in identifying transition zone injuries, while RR was superior in assessing the percentage of the joint affected by transition zone injury.

Conclusions Our results suggest that including both 3D MPR and RR MRI groupings is favorable for accurate joint visualization and well-informed treatment planning, especially given that labral injury is a main source of pain and dysfunction for FAI patients.

Keywords Hip · Labral tear · Cartilage injury · Imaging

Introduction

Femoroacetabular impingement (FAI), a common cause of hip pain in adolescents, is characterized by pathological abutment of the femoral head-neck junction with the acetabulum. FAI primarily presents as two types of deformities, cam-type [1, 2] and pincer-type, which can occur alone or co-exist in the same hip [3]. Each causes specific patterns of labral and cartilage injury [3].

Imaging is vital to diagnosis and surgical decision making in FAI. Plain radiographs and computed tomography help define bony anatomy, while magnetic resonance imaging (MRI) helps identify intra-articular cartilage and labral injuries [4]. However, the oblique orientation and curved articular surfaces of the hip joint make imaging via magnetic resonance (MR) challenging and may result in partial volume averaging or the lack of contrast between adjacent tissues [5, 6]. Furthermore, articular cartilage is relatively thin, adding to the difficulty in accurately diagnosing cartilage damage [5].

High-resolution MRI, 3-dimensional (3D) MRI, or a combination of both helps improve hip joint imaging protocols. High-resolution (HR), an ever-changing term, indicates decreased pixel or voxel size to improve an image's spatial

✉ Michael Fadell
mfadell@stanford.edu

[1] Children's Hospital Colorado, Aurora, CO, USA

[2] Department of Orthopedic Surgery, University of Colorado School of Medicine, Aurora, CO, USA

[3] Department of Radiology, University of Colorado School of Medicine, Aurora, CO, USA

Table 1 MRI protocol parameters

	Cor T1	Cor STIR	AX PD FS	Cor PD 3D	Cor PD HR	Sag PD HR	AX PD HR	AX T2 hips	AX T2 knee
TR (ms)	722.9	5639.5	4178.3	1300	2400	3992	3992	3000	3000
TE (ms)	5.9	50	24	36.6	27	30	30	90	90
TI (ms)	NA	220	NA	NA	NA	NA	NA	NA	NA
BW (kHz)	185	77	108	83	85	369	369	65	65
ETL	7	15	15	70	15	15	15	21	21
Flip (deg)	90	90	90	90	90	90	90	90	90
NEX	1	1	1	2	2	2	2	1	1
FOV (mm × mm)	351 × 351	350 × 350	350 × 350	180 × 180	130 × 130	160 × 120	160 × 120	300 × 300	300 × 300
Matrix (acq)	381 × 500	261 × 353	261 × 353	212 × 212	207 × 360	380 × 122	380 × 122	238 × 300	238 × 300
Matrix (rec)	528 × 528	448 × 448	480 × 480	384 × 384	384 × 384	480 × 480	480 × 480	384 × 384	384 × 384
Slice Thickness (mm)	3	3	3	0.84	2.5	3	3	5	5
Slice Gap (mm)	0.3	0.3	0.3	−0.42	0.25	0.3	0.3	1	1
NPW (no phase wrap) or phase oversampling	Y	Y	Y	Y	Y	Y	Y	Y	Y
Freq Dir	S/I	S/I	R/L	S/I	S/I	A/P	A/P	A/P	A/P
Est. time (min:sec)	3:54	2:40	4:25	7:51	3:55	3:54	3:54	0:54	0:54

resolution, currently on the order of 0.5 mm per pixel for 2-dimensional (2D) MRI [7]. Especially beneficial for multiplanar reformatted (MPR) images, 3D MRI utilizes isotropic voxels, or voxels with the same dimensions in the x, y, and z planes, allowing resultant images to be reconstructed in any plane [8]. Radial images, reformatted from 3D acquisitions to obtain images at prescribed angular intervals (i.e., 10 to 20°) perpendicular to the femoral neck axis, are used to produce a set of images over the circumference of the femoral head-neck junction and to evaluate the acetabulum and labrum [5, 9–11].

MRI sequences identifying pathology in the labrum, transition zone cartilage, and true acetabular cartilage must be accurate and timely. For this study, we developed an FAI Hip MRI protocol that includes the following sequences: (1) 2D axial proton density (PD) imaging with individual axial, sagittal, and coronal plane acquisitions (2D); (2) 3D PD imaging with multiplanar reformats (3D MPR); and (3) radially reformatted (RR) images post-processed from 3D PD acquisitions (Table 1). Our study aims to compare these three MR acquisitions in their ability to evaluate the labrum, chondrolabral junction, and articular cartilage of the hip joint in adolescents with FAI. We hypothesized RR PD imaging would have the highest accuracy in detecting labral tears and 2D PD imaging would have the highest accuracy in detecting cartilage injury.

Table 2 Beck classification system for labral and transition zone cartilage injury

Grade	Labral classification	Transition zone classification
0	Normal	Normal, no pathology
1	Degeneration	Malacia/softening
2	Full Thickness Tear	Debonding, carpet/wave sign
3	Detachment	Cleavage/flap
4	Ossification	Defect

Materials and methods

The study protocol was approved by the Colorado Multiple Institutional Review Board. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Thirty-three consecutive cases of FAI, meeting clinical criteria, and having undergone pre-operative MRI followed by operative management were included in the study. All included patients had undergone pre-operative hip MR with 2D HR PD coronal, sagittal, and axial sequences; 3D PD sequence with multiplanar reformats (MPR) in the coronal, sagittal, and axial planes; and radially reformatted (RR) images constructed from the 3D PD data set and acquired on a 3 Tesla (T) magnet. All studies were completed on a Philips MRI machine. Patients with inadequate surgical notes or hip MRI not including the specific sequences mentioned above were excluded.

For each included hip MRI, the sequences were grouped as follows: (1) 2D HR PD images independently acquired in the coronal, sagittal, and axial planes (named

Table 3 Outerbridge classification system for acetabular cartilage injury

Level	Classification
0	Normal
1	Softening
2	Partial thickness defect, fissures which do not reach subchondral bone or exceed 1.5 mm in diameter
3	Fissuring to subchondral bone or exceeds 1.5 mm in diameter
4	Exposed subchondral bone

2D); (2) 3D PD images acquired in the coronal plane with MPR's in the coronal, sagittal, and axial planes (named 3D MPR); and (3) PD RR images created from the 3D PD data set (named RR) (with the sagittal MPR images used as a reference to help determine the direction of rotation) (Table 1). Each of the three groupings of MR sequences was then evaluated for the following: injury to the (1) labrum, (2) transition zone cartilage, and (3) true acetabular cartilage. The transition zone cartilage was defined as the hyaline cartilage located less than 5 mm away from the labrum, whereas the true acetabular cartilage included all deeper articular cartilage [1, 2].

The grouped 2D, 3D MPR, and RR MRI images for each MRI were independently reviewed, in random order to avoid bias, by two board-certified musculoskeletal radiologists with 5 and 7 years of experience. Readers were blinded to the

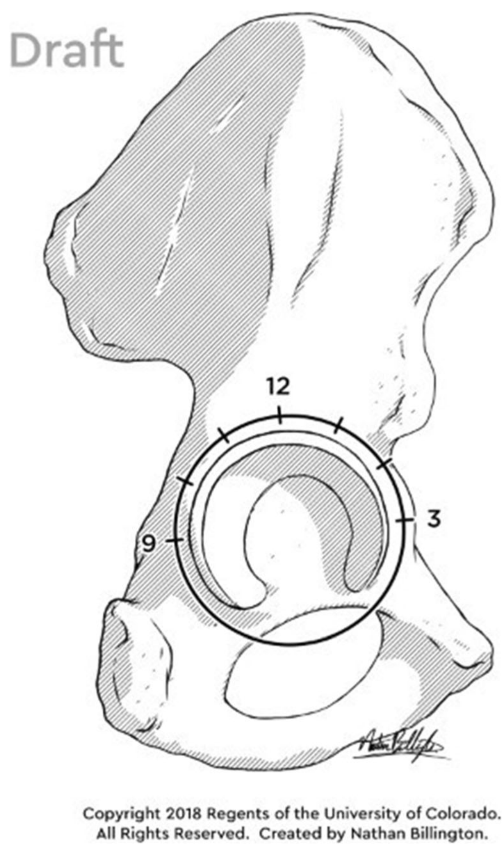

Fig. 1 Orientation of clock face on acetabular rim used for location of labral, transition zone cartilage defects, and acetabular cartilage defects

results of arthroscopy at the time of review. The Beck classification for labral and transition zone cartilage injury in FAI was utilized with scoring from 0 to 4 (Table 2) [12]. The true acetabular cartilage was graded based on the Outerbridge classification with scoring from 0 to 4 (Table 3) [13]. The location and percentage of hip joint affected by the labral, transition zone, and true acetabular cartilage injury, when present, was also recorded. The location of the injury was assessed from 11 to 3 o'clock sectors based on the clock-face method of visualizing the acetabulum (Fig. 1) [14–16]. Percentage of hip joint affected was defined as the total number of consecutive clock levels affected by the injury which was converted into a percentage based on the following equation: [number of consecutive affected levels/12].

Intra-operative images and operative reports for all patients were then reviewed by a single orthopedic surgeon for the purpose of defining the presence of labral, transition zone, and true acetabular cartilage pathology.

Statistical methods

Using the intra-operative visualization as the gold-standard, the sensitivity, specificity, and accuracy of the three separate methods of MRI sequences in identifying the presence of

Table 4 Prevalence of intra-articular injuries by position, as noted at arthroscopy

Level	Labrum		Transition zone		Acetabular cartilage	
	N	%	*N*	%	*N*	%
1 o'clock	28	84.8%	25	75.8%	2	6.1%
2 o'clock	30	90.9%	26	78.8%	2	6.1%
3 o'clock	21	63.6%	21	63.6%	1	3.0%
4 o'clock	0	0.0%	0	0.0%	0	0.0%
5 o'clock	0	0.0%	0	0.0%	0	0.0%
6 o'clock	0	0.0%	0	0.0%	0	0.0%
7 o'clock	0	0.0%	0	0.0%	0	0.0%
8 o'clock	0	0.0%	0	0.0%	0	0.0%
9 o'clock	0	0.0%	0	0.0%	1	3.0%
10 o'clock	3	9.1%	3	9.1%	3	9.1%
11 o'clock	17	51.5%	21	63.6%	1	3.0%
12 o'clock	25	75.8%	24	72.7%	4	12.1%

Table 5 Classification of pathology in 11–3 o'clock region-based on intra-operative visualization

	N	%
Labral tears		
Normal	1	3.0%
Degeneration	1	3.0%
Full thickness tear	9	27.3%
Detachment	21	63.6%
Ossification	1	3.0%
Transition zone		
Normal	1	3.0%
Softening	5	15.2%
Debonding/carpet sign	17	51.5%
Cleavage/flap	10	30.3%
Defect	0	0.0%
Acetabular cartilage		
Normal	22	66.7%
Softening	5	15.2%
Partial thickness defect < 1.5 cm	4	12.1%
Fissure/defect > 1.5 cm	2	6.1%
Exposed subchondral bone	0	0.0%

labral, transition zone, and true acetabular cartilage injuries were assessed from the 11 o'clock to 3 o'clock positions. This region of the hip was selected as it was associated with highest prevalence of intra-articular pathology noted at arthroscopy (Table 4). Bland-Altman methods were used to estimate agreement between percentage of the hip affected by the injury as measured by the MRI methods relative to intra-operative visualization. The bias or the mean difference between the MRI-based method and arthroscopic visualization, as well as the limits of agreement, was calculated for each of the three methods.

Results

Thirty three hips (13 female, 20 male) were included in the sample. Twenty-six of the hips were diagnosed with cam-type impingement (1 pincer-type, 6 mixed-type) and the average age at the time of surgery was 16.6 years (range: 12.7–24 years). On average, 17.9 weeks elapsed between pre-operative imaging and operative management (range: 0.714–86.0 weeks). Labral and transition zone injuries were most frequently identified at the 2 o'clock position. True acetabular cartilage injuries were most frequently identified at the 12 o'clock position (Table 4). The classification of the severity of pathology and the proportion of hip affected by the injuries are described in Tables 5 and 6. Figure 2 shows intra-operative findings of a patient included in this study with a labral tear and transition zone cartilage injury (Fig. 2a, b) and the corresponding MRI in radial reformatted image (Fig. 2c) and MPR images (Fig. 2d, e, f). Figure 3 shows the intra-operative (Fig. 3) and MRI findings of another patient included in the study with a transition zone cartilage injury with the corresponding radially reformatted image (Fig. 3b), MPR image (Fig. 3c), and HR image (Fig. 3d). On average, an imaging study took 32 min and 21 s to accomplish.

Table 6 Size of injury/percentage of hip joint based on intra-operative visualization

	Mean	St dev.
Labrum	0.31	0.13
Transition zone	0.30	0.17
Acetabular cartilage	0.04	0.10

Labral injuries

For labral injuries, the 3D MPR and RR MRI groupings were associated with highest sensitivity and accuracy in assessing the presence of an injury between the 11 and 3 o'clock positions (Table 7). The 3D MPR grouping demonstrated the lowest levels of bias (smallest mean difference between MRI evaluation and surgical evaluation) in assessing the size of the injury (Table 8).

Transition zone injuries

The 2D MRI grouping was the most accurate in identifying the presence of transition zone injuries between the 11 and 3 o'clock positions (Table 7). The RR grouping demonstrated lower levels of bias when assessing the size of the transition zone injury relative to the other groupings (Table 8).

True acetabular cartilage injuries

The 3D MPR grouping was the most accurate MRI sequence in identifying the presence of acetabular cartilage injuries in the 11–3 o'clock positions (Table 7). The RR grouping was associated with a lower level of bias when assessing the size of the acetabular cartilage injury relative to the other groupings (Table 8).

Discussion

FAI, a morphological abnormality of the acetabulum and proximal femur, can cause hip pain and dysfunction while being linked to early osteoarthritis in otherwise healthy hips [3, 12, 17]. FAI often produces the most severe damage to the acetabular labrum and cartilage in the anterosuperior region [3, 6, 8].

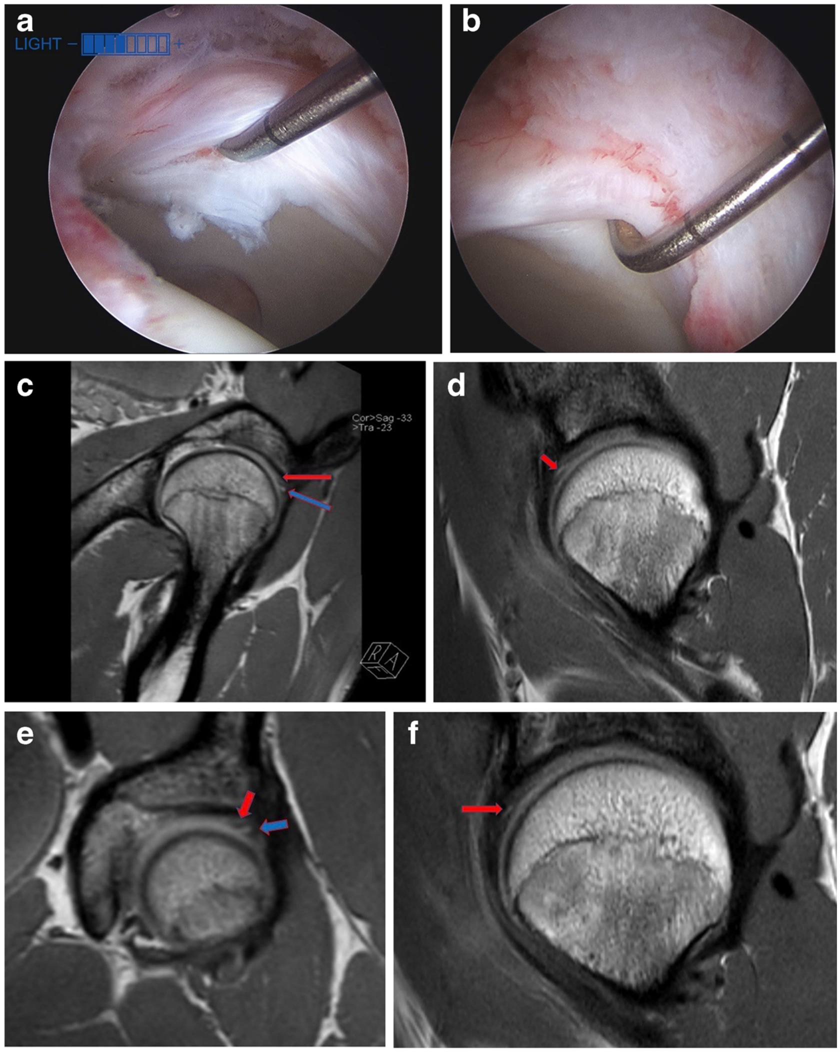

Fig. 2 **a** Intra-operative image of a 16-year-old male's left hip with Beck grade 3 (flap) transition zone chondral injury from 1 to 3 o'clock (seen inferior to probe) as part of Beck grade 3 (detached at chondrolabral junction) labral tear (seen superior to probe). **b** Intra-operative image of a 16-year-old male's left hip with Beck grade 2 (debonding/carpet or wave sign) transition zone chondral injury from 11 to 1 o'clock (seen inferior to the probe) as part of a Beck grade 3 (detached at chondrolabral junction) labral tear (seen superior to probe). **c** Corresponding radially reformatted PD image obtained from the 3D acquisition showing a Beck grade 2 (debonding/carpet or wave sign) transition zone chondral injury (red arrow) as part of a Beck grade 3 (detached at chondrolabral junction) labral tear (blue arrow) in a 16-year-old male. **d** Corresponding sagittal MPR MR imaging of a 16-year-old male with a Beck grade 2 (debonding/carpet or wave sign) transition zone cartilage injury (red arrow). **e** Corresponding coronal MPR MR imaging of a 16-year-old male with a Beck grade 2 (debonding/carpet or wave sign) transition zone chondral injury (red arrow) as part of a Beck grade 3 (detached at chondrolabral junction) labral tear (blue arrow). **f** Corresponding sagittal HR MR imaging of a 16-year-old male with a Beck grade 2 (debonding/carpet or wave sign) transition zone cartilage injury (red arrow)

Imaging assessment of bony morphology and cartilaginous pathology provides important information for orthopedic surgeons. Increased accuracy of diagnostic imaging improves clinical decision making and focuses surgical planning. MR imaging is the most common modality for evaluation of the labrum, transition zone cartilage, and true acetabular cartilage. The ideal MRI sequence would be both accurate and efficient. Therefore, we sought to determine the best sequences for evaluation of the soft tissue structures in the hip.

3D MPR and RR groupings were superior to the 2D grouping in assessing labral tears. The 3D MPR grouping had the lowest bias in assessing the size of the labral tears. Previously related studies have evaluated the accuracy of 3 T MRI and 3 T MR arthrogram to assess labral tears relative to direct visualization during arthroscopy [18–22]. Sensitivity and specificity estimates for 3 T MRI ranged between 61 and 100% and 50–100%, respectively, with one study reporting 98% accuracy [1, 18–22]. Two studies using 3 T arthrogram techniques have reported 90–95% sensitivity and 0% specificity in one study and 84% specificity in the other. Only one of these studies using 3 T machines included radially reformatted sequences in their image evaluation, while the others utilized

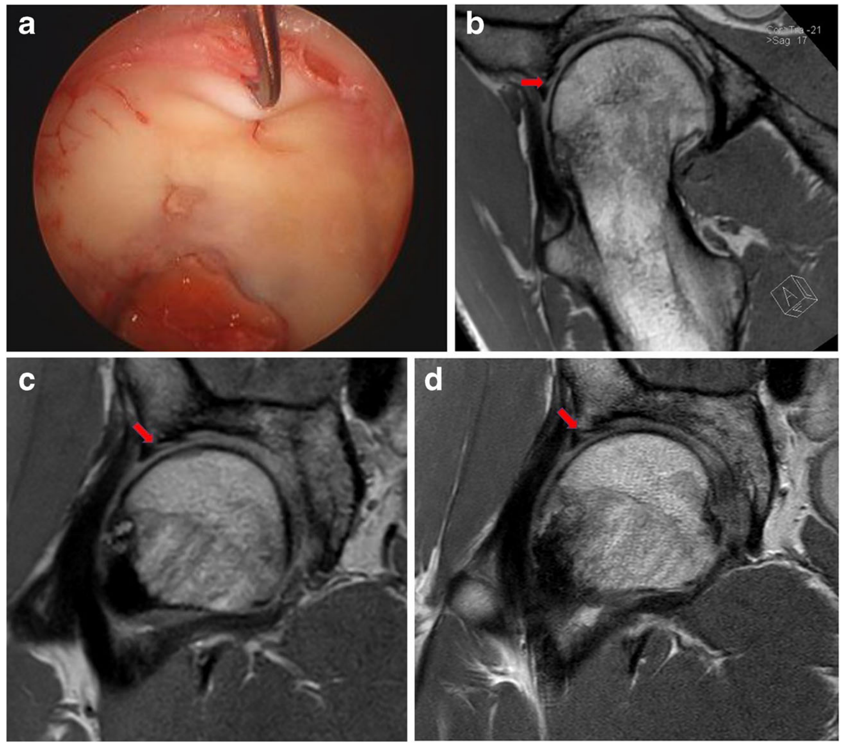

Fig. 3 **a** Intra-operative image of a right hip with Beck grade 3 (flap) transition zone chondral injury from 12 to 2 o'clock (seen inferior to the probe). **b** Corresponding radially reformatted PD image of a 23-year-old male obtained from the 3D acquisition showing Beck grade 3 (flap) transition zone chondral injury (red arrow). **c** Corresponding coronal MPR MR imaging of a 23-year-old male with a Beck grade 3 (flap) transition zone cartilage injury (red arrow). **d** Corresponding coronal HR MR imaging of a 23-year-old male with a Beck grade 3 (flap) transition zone cartilage injury (red)

only coronal, sagittal, and axial 2D sequences. Therefore, these studies have focused on the utility of 3 T MR and 3 T MR arthrography for the detection of labral tears, but none has included 3D MR imaging, and none has directly compared 3D MR and radially reformat sequences to one another. Our results for 3D MPR and RR sequences performed similarly with 98.4% sensitivity, 0% specificity, and 95.5% accuracy.

The 3D MPR as well as RR groupings was acquired in the same fashion. They may be more sensitive and accurate in assessing the labrum than other structures because the labrum is a low-signal intensity structure with less water content than the adjacent transition zone and acetabular cartilage resulting in an improved contrast resolution. Additionally, the 3D MPR sequence has a higher signal to noise ratio (SNR) than 2D which is attributed to both the slightly larger voxel size as well as the greater number of measurements intrinsic to this type of acquisition, a factor of the number of phase encoding steps in the slice direction.

For the transition zone cartilage, the 2D grouping was the best in assessing injury while the RR grouping showed the lowest agreement bias; however, our results showed that all three groupings performed relatively poorly. Only one other study has evaluated 3 T MR for transition zone cartilage injury; however, this study included labral and cartilage tears at the transition zone, making this difficult to compare with our report of chondral lesions at the transition zone only [18]. In this study, they found 56% agreement between 3 T MR and arthroscopy, similar to our results with 66.7% sensitivity, 85.2% specificity, and 81.8% accuracy with 2D imaging, which was the most accurate of the three sequences in our study. There were no studies utilizing 3 T arthrogram to diagnose transition zone cartilage injuries to compare in the literature.

The 3D MPR grouping demonstrated slight superiority to the other two groupings for identifying true acetabular injuries; however, all three groups performed relatively poorly.

Table 7 Accuracy in identifying intra-articular pathology

	2D Images			3D MPR Images			RR Images		
	Sens.	Spec.	Acc.	Sens.	Spec.	Acc.	Sens.	Spec.	Acc.
Labrum	93.8%	0.0%	90.9%	98.4%	0.0%	95.5%	98.4%	0.0%	95.5%
Transition Zone	66.7%	85.2%	81.8%	41.7%	74.1%	68.2%	58.3%	77.8%	74.2%
Acetabular Cartilage	31.5%	100.0%	43.9%	42.6%	66.7%	47.0%	38.9%	58.3%	42.4%

Sens sensitivity, *Spec* specificity, *Acc* accuracy or proportion of agreement

Table 8 Agreement regarding injury size or percentage of hip joint affected by injury

	2D images			3D MPR images			RR images		
	Bias	LL	UL	Bias	LL	UL	Bias	LL	UL
Labrum	− 0.126	− 0.400	0.148	− 0.098	− 0.347	0.150	− 0.107	− 0.385	0.171
Transition Zone	− 0.266	− 0.606	0.073	− 0.242	− 0.609	0.124	− 0.241	− 0.637	0.155
Acetabular Cartilage	− 0.014	− 0.209	0.182	− 0.003	− 0.226	0.221	− 0.006	− 0.197	0.184

LL, lower limit of agreement; *UL*, upper limit of agreement

Three previous studies have utilized standard 2D sequences with 3 T MR for evaluation of the acetabular cartilage. Results ranged from 59 to 94% sensitivity and 67–100% specificity and one reporting 56% agreement [18–20]. Although not statistically evaluated, one of these studies found increased sensitivity in imaging after including a radial cut along with sagittal, coronal, and axial formats in their evaluation, which they attributed to the ability of a radially reformatted sequence to obtain more in-plane images of the curved acetabular surface [19]. One study has also compared 3 T arthrography with arthroscopy for evaluation of the acetabular cartilage, with 71–81% sensitivity and 82–91% specificity between two readers [20]. Our results were somewhat less accurate compared with these previous reports using both 3 T MR and 3 T MR arthrography (42.6% sensitivity, 66.7% specificity, 47% accuracy). The decreased level of accuracy in our study is likely attributable to differences in our assessment method. We considered both the injury as well as the location of the injury. Thus, in our study, a high level of accuracy depends on both the orientation of the image orientation (clock face is oriented correctly) as well as the identification of the injury. We believe this approach is more clinically relevant as surgical planning depends on an accurate assessment of both the location and intra-articular injuries.

We anticipated more favorable results with the 2D sequences when compared with the 3D MPR and RR groupings in the evaluation of articular cartilage damage given the higher in-plane resolution with 2D acquisitions than with the 3D acquisitions. In addition, the heavier T1 weighting associated with the 2D sequence, due to a significantly shorter repetition time (TR), in general allows for better evaluation of high-water content structures such as articular cartilage. However, as our results indicate, this hypothesis was not completely validated. One possible explanation for this is that the cartilage injuries in this relatively young cohort were few and not very severe (of the 6 cartilage injuries, only 2 were > 1.5 cm). The sensitivity of MRI in detecting these minor abnormalities was not high in our current sequencing parameters. Therefore, in this population compared with an older population, this low sensitivity may be more of a concern.

Our study included several additional limitations. Our sample was not random as each patient underwent a history and physical exam prior to imaging. Selection bias is possible as each patient met preliminary diagnostic criteria for FAI and thus was more likely to have cartilage or labral damage. There was also intrinsic selection bias as the orthopedic surgeons were not blinded to pre-operative imaging before choosing to proceed with operative intervention; their physical examination as well as evaluation of imaging most likely dictated their decision to continue with surgery. Additionally, our study sample did not include a control group without labral or cartilage injury, as operative assessment would have been unethical. We also did not control for the time from MRI to arthroscopy, which ranged from less than a week to over a year. The abnormal labrum and/or cartilage may have undergone some change during this time, limiting the accuracy of MRI.

While the 3D PD sequence with multiplanar reformats as well as RR images performed well in the evaluation of injury to the labrum, all sequences were relatively poor at detecting injury to both transition zone and true acetabular cartilage. Future research and possible options for improvement include: (1) improve the spatial resolution of the 2D sequence by decreasing both the slice thickness and slice gap while keeping pixel size relatively constant; and 2) decrease the voxel size of 3D PD sequence to improve spatial resolution. The second option could obviate the need for a separate 2D acquisition altogether, replacing these sequences with multiplanar reformats as well as radially reformatted images constructed from the 3D PD, allowing for an overall shorter protocol.

Conclusions

Given that labral injury is a primary source of pain and dysfunction for patients with FAI, we sought to determine an efficient and accurate MR imaging sequence for evaluating the morphology of the labrum, transition zone cartilage, and true acetabular cartilage. Including both 3D MPR and RR MRI groupings is favorable for accurate visualization of the hip joint and may help guide diagnosis and treatment planning.

Compliance with ethical standards

The study protocol was approved by the Colorado Multiple Institutional Review Board. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

References

1. Crespo-Rodriquez AM, de Lucas Villarrubia JC, Pastrana-Ledesma MA, Millan SI, Padron M. Diagnosis of lesions of the acetabular labrum, of the labral-chondral transition zone, and of the cartilage in femoroacetabular impingement: correlation between direct magnetic resonance arthrography and hip arthroscopy. Radiologia. 2015;57(2):131–41.
2. James SL, Ali K, Malara F, Young D, O'Donnell J, Connell DA. MRI findings of femoroacetabular impingement. AJR Am J Roentgenol. 2006;187(6):1412–9.
3. Ganz R, Parvizi J, Beck M, Leunig M, Notzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. Clin Orthop Relat Res. 2003;417:112–20.
4. Bittersohl B, Hosalkar HS, Apprich S, Werlen SA, Siebenrock KA, Mamisch TC. Comparison of pre-operative dGEMRIC imaging with intra-operative findings in femoroacetabular impingement: preliminary findings. Skelet Radiol. 2011;40(5):553–61.
5. Naraghi A, White LM. MRI of labral and chondral lesions of the hip. Am J Roentgenol. 2015;205(3):479–90.
6. Rakhra KS. Magnetic resonance imaging of acetabular labral tears. J Bone Joint Surg Am. 2011;93(Suppl 2):28–34.
7. Potter HG, Schachar J. High resolution noncontrast MRI of the hip. J Magn Reson Imaging. 2010;31(2):268–78.
8. Omar IM, Blount KJ. Magnetic resonance imaging of the hip. Top Magn Reson Imaging. 2015;24(4):165–81.
9. Li AE, Jawetz ST, Greditzer HG, Burge AJ, Nawabi DH, Potter HG. MRI for the preoperative evaluation of femoroacetabular impingement. Insights Imaging. 2016;7(2):187–98.
10. Ziegert AJ, Blankenbaker DG, De Smet AA, Keene JS, Shinki K, Fine JP. Comparison of standard hip MR arthrographic imaging planes and sequences for detection of arthroscopically proven labral tear. AJR Am J Roentgenol. 2009;192(5):1397–400.
11. Petchprapa CN, Dunham KS, Lattanzi R, Recht MP. Demystifying radial imaging of the hip. RadioGraphics. 2013 May;33(3):E97–112.
12. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip. J Bone Joint Surg Br. 2005;87(7):1012–8.
13. Outerbridge RE. The etiology of chondromalacia patellae. J Bone Joint Surg Br. 1961;43B(4):752–7.
14. Blankenbaker DG, De Smet AA, Keene JS, Fine JP. Classification and localization of acetabular labral tears. Skelet Radiol. 2007;36(5):391–7.
15. Philippon MJ, Michalski MP, Campbell KJ, Goldsmith MT, Devitt BM, Wijdicks CA, et al. An anatomical study of the acetabulum with clinical applications to hip arthroscopy. J Bone Joint Surg Am. 2014 Oct 15;96(20):1673–82.
16. Philippon MJ, Stubbs AJ, Schenker ML, Maxwell RB, Ganz R, Leunig M. Arthroscopic management of femoroacetabular impingement: osteoplasty technique and literature review. Am J Sports Med. 2007;35(9):1571–80.
17. Byrd JW, Jones KS, Gwathmey FW. Femoroacetabular impingement in adolescent athletes: outcomes of arthroscopic management. Am J Sports Med. 2016;44(8):2106–11.
18. Crespo-Rodríguez AM, de Lucas-Villarrubia JC, Pastrana-Ledesma M, Hualde-Juvera A, Méndez-Alonso S, Padron M. The diagnostic performance of non-contrast 3-tesla magnetic resonance imaging (3-T MRI) versus 1.5-tesla magnetic resonance arthrography (1.5-T MRA) in femoro-acetabular impingement. Eur J Radiol. 2017 Mar;88:109–16.
19. Linda DD, Naraghi A, Murnaghan L, Whelan D, White LM. Accuracy of non-arthrographic 3T MR imaging in evaluation of intra-articular pathology of the hip in femoroacetabular impingement. Skelet Radiol. 2017;46(3):299–308.
20. Magee T. Comparison of 3.0-T MR vs 3.0-T MR arthrography of the hip for detection of acetabular labral tears and chondral defects in the same patient population. Br J Radiol. 2015;88(1053):20140817.
21. Sutter R, Zubler V, Hoffmann A, Mamisch-Saupe N, Dora C, Kalberer F, et al. Hip MRI: how useful is intraarticular contrast material for evaluating surgically proven lesions of the labrum and articular cartilage? AJR Am J Roentgenol. 2014;202:160–9.
22. Tian CY, Wang JQ, Zheng ZZ, Ren AH. 3.0 T conventional hip MR and hip MR arthrography for the acetabular labral tears confirmed by arthroscopy. Eur J Radiol. 2014;83:1822–7.