Received:
25 May 2018

Revised:
02 July 2018

Accepted:
24 July 2018

<https://doi.org/10.1259/bjr.20180474>

Cite this article as:

Yan K, Xi Y, Sasipongnan C, Zerr J, Wells JE, Chhabra A. Does 3DMR provide equivalent information as 3DCT for the pre-operative evaluation of adult Hip pain conditions of femoroacetabular impingement and Hip dysplasia?. *Br J Radiol* 2018; **91**: 20180474.

FULL PAPER

Does 3DMR provide equivalent information as 3DCT for the pre-operative evaluation of adult Hip pain conditions of femoroacetabular impingement and Hip dysplasia?

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Objective: Femoroacetabular impingement (FAI) and hip dysplasia (HD) are frequently evaluated by isotropic CT (3DCT) for preoperative planning at the expense of radiation. The aim was to determine if isotropic MRI (3DMR) imaging can provide similar quantitative and qualitative morphological information as 3DCT.

Methods: 25 consecutive patients with a final diagnosis of FAI or HD were retrospectively selected from December 2016–December 2017. Two readers (R1, R2) performed quantitative angular measurements on 3DCT and 3DMR, blinded to the diagnosis and each other's measurements. 3DMR and 3DCT of the hips were qualitatively and independently evaluated by a radiologist (R3), surgeon (R4), and fellow (R5). Interobserver and intermodality comparisons were performed.

Results: The ICC was good to excellent for all measurements between R1 and R2 (ICC:0.60–0.98) and the

majority of intermodality measurements for R1 and R2. Average inter-reader and inter-modality PABAK showed good to excellent agreement for qualitative reads. On CT, all alpha angles (AA) were significantly lower in dysplasia patients than in cam patients ($p < 0.05$). All lateral center-edge angle (LCEA) were significantly lower in dysplasia than in cam patients ($p < 0.05$). On MR, AA at 12, 1, and 2 o'clock, and LCEA at center were significantly lower in dysplasia patients than in cam patients ($p < 0.05$).

Conclusion: 3DMR offers similar qualitative and quantitative analysis as 3DCT in adult painful hip conditions.

Advances in knowledge: 3DMR has good potential to replace 3DCT and serve as a one-stop modality for bone and soft tissue characterizations in the pre-operative evaluation of FAI and HD.

INTRODUCTION

Chronic hip pain accounts for nearly 10% of all visits to sports medicine clinicians, and causes such as femoroacetabular impingement (FAI), hip dysplasia (HD), labral tears, muscle strains, and osteoarthritis are the most frequent encountered pathologies.^{1,2} Recently, HD and FAI are suggested as risk factors for the development of osteoarthritis; however, the underlying mechanism leading to pathology is not fully understood.³ Early diagnosis and treatment of these hip conditions may improve patient prognosis.⁴

For diagnosis and pre-operative evaluation, radiographs, CT, and MR imaging of the hip are frequently obtained.⁵ 3-dimensional isotropic CT (3DCT) is most often used in the pre-surgical planning to demonstrate proximal femoral

and acetabular anatomy, and the technique has been shown to improve surgical results.^{6,7} Various measurements have been obtained to evaluate the morphology of the proximal femur, including acetabular version (AV), lateral center-edge angle (LCEA), femoral neck angle (FNA), and alpha angle (AA).⁸ Most of the patients who are affected by these pathologies and imaged are young, and the CT radiation dose to the pelvis is approximately 5mSv to 7mSv.⁹ In addition, CT without intra-articular contrast does not offer great visualization of the labrum and cartilage, but MRI with or without intra-articular contrast is the gold standard for soft tissue evaluation around the hip.¹⁰ MRI is often ordered in conjunction with 3DCT to evaluate these structures. 3DMR sequence is routinely obtained in our practice during such scans, which takes additional 4–7min of acquisition time. These images acquired in volumetric fashion

like 3DCT mitigate partial-volume artifacts and allow high-resolution evaluation of the joint in multiple planes. With isotropic 3DMR images, it takes about 15 to 30 min to post-process the MR data and create 3D volume rendered images (11). Such scans have been shown to offer similar bone surface reconstructions as 3DCT reconstructions, which is a significant advancement considering that labrum and cartilage can also be evaluated in the same setting. Thus, 3DMR imaging serves as a one-stop-shop for both bony and soft tissue assessment of the hip.^{11–17} While CT imaging is much quicker, MR imaging saves radiation dose to the young, radiation-sensitive patient population imaged for internal hip derangements. In preliminary studies on hip dysplasia, 3DMR has shown excellent inter-rater reliability for isolated bony measurements of the femoral head.^{8,14} However, some hip dysplasia patients also exhibit femoral head and neck abnormalities, and it is not known whether those patients can be as accurately analyzed with 3DMR as 3DCT.⁶ None of the previous studies compared the measurements of 3DMR imaging with the measurements of 3DCT in these common hip pain disorders. If 3DMR imaging does provide similar results as 3DCT, then the use of 3DCT could be eliminated from the pre-operative evaluation of such disorders to reduce cost, radiation, patient discomfort, and time.

This study was aimed at comparing femoroacetabular anatomy on 3DCT and 3D MRI using both qualitative analysis and quantitative measurements along with evaluation of inter-reader reliability. We hypothesized that the diagnosis of FAI and HD can be reliably performed using 3DMR and that the quantitative measurements on 3DMR imaging will not be significantly different to those obtained from 3DCT.

METHODS AND MATERIALS

This is a retrospective cross-sectional study following institutional review board approval. The informed consent was waived.

Patients

A consecutive series of patients who presented from December 2016 to December 2017 for hip pain for preoperative evaluation at our university hospital and received an MR arthrogram on 1.5T or 3T scanners were included. All patients must also have had a CT scan during the same time as part of their pre-surgical assessment. The patients had either a final diagnosis of hip dysplasia or FAI. The patients were excluded if they had prior surgery of the hip, metal artifacts on imaging, or did not receive both CT and MRI scans (flow chart in [Figure 1](#)). Patient demographic data including age, sex, body mass index (BMI),

Figure 1. Patient selection flowchart detailing the number of patients excluded for various reasons, including lack of a valid CT scan or prior surgery to the hip.

Table 1. Reading scale for all qualitative reads

Reading variable	Scale	Interpretation of scale
Dysplasia	0	Normal head and acetabulum less than 20% under covered
	1	Definite shallow acetabulum with more than 20% under covered or misshapen head
	2	Unsure – possible shallow acetabulum or less than 20% under coverage of head
Bump	0	Normal concavity at femoral head and neck junction
	1	Definite lack of normal offset or bony protuberance at the femoral head and neck junction
	2	Unsure – possible lack of offset at femoral head and neck junction
Pincer	0	Less than 50% of head inside the socket
	1	Definitely more than 50% of head inside the socket
	2	Unsure – possibly 50% of head inside the socket
Quality	1	All margins are discernable without motion artifacts and a confident diagnosis can be made
	2	Less than 25% of margins are obscured or not well defined but does not affect the diagnosis
	3	25 to 50% of margins are obscured or not well-defined and it affects the diagnosis
	4	Greater than 50% of the margins are obscured and reconstruction is non-diagnostic

presenting symptoms, Tonnis grade, physical examination findings, and types of surgeries, if they received surgery, were recorded (Table 1). The final diagnosis of FAI or dysplasia was established by an experienced orthopedic sports surgeon based on the history, physical examination, imaging findings, and surgical findings.

Imaging

All patients had uniform CT pelvis imaging on multi slice CT scanners with a beam collimation of 0.625mm from L5 level to the lesser trochanters covering both hips with the patients in supine position and feet in neutral position and toes pointing upwards. The MR imaging was performed using a cardiac coil. On 3T MRI (Achieva, Ingenia, Philips, The Best, Netherlands), 3D nonfat suppressed coronal intermediate-weighted imaging (TR- 1100 ms, TE-40 ms, voxel- 0.7 mm isotropic, fat suppression- frequency selective, acquisition time- 7min) was used and on 1.5T imaging, 3D volume interpolated breath-hold imaging (TR- 7.67ms, TE-2.88ms, voxel- 1.0mm isotropic, acquisition time- 4min) was used. The 3D imaging was obtained without interpolation or interslice gap.

Image analysis

The images were loaded on an independent software, Tera Recon (Aquarius Intuition, Foster City, CA). Two medical student readers (R1 and R2) independently performed all the measurements, trained by an experienced musculoskeletal radiologist. A standard clock face nomenclature was adopted for localization around the femoral head-neck junction with the anterior and superior locations designated at 3 o'clock and 12 o'clock, respectively.¹⁸ The measurements included the lateral center edge angle (LCEA) at the anterior, center, and posterior margins of the acetabulum, the anterior center edge angle (VCA), acetabular versions at 1, 2, and 3 o'clock, femoral neck-shaft angle, and alpha angles at 12, 1, 2, and 3 o'clock. The optimal method for measuring these angles have been described in previous papers^{8,19} and shown in Figure 2. For training purposes, 5 scans

were measured by the readers together before the independent measurements. CT and MR measurements were done on separate days, with a week gap. The two readers were blinded to the CT measurements when obtaining MR measurements. The readers were blinded to the final diagnoses.

Qualitative analysis

3D reconstructions were performed on the independent Aquarius (TeraRecon, Foster city, CA) software. For CT, soft tissue algorithm volume scans were used to produce 3D volume rendered and multiplanar reconstructions. For MR, 3D volume rendered reconstructions were constructed using a free hand semi-automated technique described previously.¹¹ One fellowship trained experienced musculoskeletal radiologist (R3), one orthopedic hip surgeon (R4), and one musculoskeletal radiology fellow (R5) independently evaluated the 3-D volume rendered reconstructions from CT and MRI and evaluated the hip anatomy with regards to the diagnosis of dysplasia and femoral bump. The reading scale used for dysplasia, femoral bump, pincer, and quality of image is described in Table 1. The three readers were blinded to each other's evaluations and they read the CT and MRI reconstructions in separate times.

Statistical analysis

Descriptive statistics for all variables were obtained. Prevalence-adjusted bias-adjusted kappa (PABAK) was used to assess the inter-reader and intermodality agreements.²⁰ Wilcoxon Rank sum tests were used to test the association between CT/MR measurements and the diagnosis (CAM/combined vs dysplasia). Isolated Pincer was excluded from the Wilcoxon Rank sum analysis due to the small sample size. *p* value of less than 0.05 was considered statistically significant. Analysis was done in SAS 9.4 (SAS Institute Inc., Cary, NC). The Cicchetti scale (less than 0.40 = poor, 0.40 to 0.59 = fair, 0.60 to 0.74 = good, 0.75 to 1.00 = excellent) was used for categorization of intraclass correlation coefficient (ICC) and kappa.²¹

Figure 2. CT (a) sample angle measurements from left to right—LCEA at the anterior (dotted line), center (dashed line), and posterior (solid line) margin, sample LCEA measurement at center margin; anterior center edge angle; acetabular version at 3 o'clock; femoral neck-shaft angle; alpha angle at 12 o'clock. MR (b) sample angle measurements follow the same order as CT measurements on 3D fsPDW images.

RESULTS

Patient characteristics

Table 2 summarizes the patient characteristics, history, physical examination findings, and type of surgery, if they received surgery. The patients who did not receive surgery still received all pre-operative workup, but they chose to undergo conservative treatment, *i.e.* physical therapy with follow-up in future for potential surgery. Patients with cam or combined cam/pincer deformities were significantly older than patients with dysplasia (mean age 30.1 vs 40.7 years, respectively, $p = 0.03$). Patients with cam or combined cam/pincer deformity had significantly lower BMI than patients with HD (mean BMI 22.3 kg m⁻² vs 26.6 kg m⁻², respectively, $p = 0.02$). There was no significant difference in gender or Tonnis grades between the two groups ($p > 0.05$).

CT and MR angle measurements

All angle measurements on CT and MR were completed. The ICC was good to excellent for all measurements on CT and MR between R1 and R2 (ICC: 0.60–0.98) and for the majority of intermodality measurements (Tables 3 and 4). Femoral neck-shaft angle ICC was fair for both R1 and R2. R1 had a fair intermodality agreement for AA at 3 o'clock.

3DCT and 3DMR reconstructions

All 3DCT and 3DMR images were reconstructed successfully. No incomplete data sets were encountered. The volume rendered model reconstructions of hip dysplasia and cam deformity are shown in Figures 3 and 4. For quality, no reader assigned a value of 3 or 4 (poor quality affecting diagnostic capabilities) to any of the 3DCT or 3DMR reconstructions. Theoretically, motion

artifacts may be more prevalent on 3DMR than 3DCT due to longer acquisition times with MR imaging, however these were not encountered in the study sample. R3, R4, and R5 assessed the quality of the reconstructed images, and they had excellent agreement that the majority of both 3DCT and 3DMR reconstructions were of excellent quality. For the diagnostic categories of dysplasia, cam, or pincer, no reader assigned a value of 2 (unsure) to any of the 3DCT or 3DMR reconstructions. Average inter-reader PABAK between R3, R4, and R5 showed good to excellent agreement in all the qualitative reads relating to the diagnosis on both CT and MR (average PABAK: 0.70–0.94). Average intermodality PABAK for R3, R4, and R5 also showed good to excellent agreement in all diagnostic categories (average PABAK: 0.62–0.93). For all three readers, the diagnosis based on both 3DCT and 3DMR reconstructions showed good to excellent agreement to our gold standard final diagnosis (average PABAK: 0.80 on CT and 0.72 on MR).

Accuracy of angle measurements in diagnosis

Isolated pincer was excluded from analysis due to the insufficient number of patients with that diagnosis. A combined pincer and cam deformity was grouped into the cam diagnosis. Average angle measurements of R1 and R2 were used for analysis. On CT, AA at 12, 1, 2, and 3 o'clock were significantly lower in dysplasia patients than in cam patients ($p < 0.05$). In addition, LCEA at the anterior, center, and posterior margin were significantly lower in dysplasia patients than in cam patients ($p < 0.05$). On MR, AA at 12, 1, and 2 o'clock, and LCEA at the center margin were significantly lower in dysplasia patients than in cam patients ($p < 0.05$) (Figure 5). A Bland-Altman plot for the lateral center edge angles

Table 2. Patient characteristics

Characteristic	Value
Patients (%)	25
Male	5 (20)
Female	20 (80)
Hips	33
Diagnosis (%)	
Cam	10 (30.3)
Pincer	3 (9.1)
Combined cam and pincer	2 (6.1)
Dysplasia	18 (54.5)
Mean age, years (SD)	35.1 (11.6)
Mean BMI, kg m ⁻² (SD)	24.7 (4.3)
Presenting symptom (%)	
Pain	33 (100)
Instability	23 (69.7)
Decreased ROM	9 (27.3)
Physical examination (%)	
Positive posterior wall sign	13 (39.4)
Positive crossover sign	6 (18.2)
Tonnis grade (%)	
0	17 (51.5)
1	16 (48.5)
MR scan (%)	
1.5 Tesla	7 (21.2)
3.0 Tesla	26 (78.8)
Received surgery (%)	13 (39.4)
Labral repair	10 (30.3)
PAO	5 (15.2)
Osteochondroplasty	9 (27.3)
Total arthroplasty	1 (3)

PAO, periacetabular osteotomy; ROM, range of motion; SD, standard deviation;

and the alpha angles is displayed in [Figure 6](#). All other angles measured did not show significant difference between cam and dysplasia.

DISCUSSION

FAI and HD are common pathologic conditions seen in young adults presenting with similar hip symptoms including pain as well as lack of normal offset at femoral head and neck junction but are surgically managed differently. Proper diagnosis and timely management are essential, since osteoplasty of an incongruent head and neck junction in HD can lead to inadvertent iatrogenic long-term instability. 3DCT is most often used for accurate visualization of the bony anatomy and calculation of various angles for pre-operative planning in FAI and HD.^{22–25}

Table 3. ICC values for Reader 1 vs Reader 2 on various angle measurements

Variable	ICC	95%CI	
CT LCE anterior	0.86	0.73	0.93
CT LCE posterior	0.87	0.75	0.93
CT LCE center	0.91	0.83	0.96
CT anteroposterior center edge	0.89	0.78	0.94
CT AV 1	0.90	0.80	0.95
CT AV 2	0.95	0.90	0.97
CT AV 3	0.92	0.85	0.96
CT Femoral neck shaft	0.82	0.67	0.91
CT Alpha Angle 12	0.78	0.59	0.88
CT Alpha Angle 1	0.78	0.60	0.89
CT Alpha Angle 2	0.69	0.46	0.84
CT Alpha Angle 3	0.60	0.32	0.78
MR LCE anterior	0.91	0.82	0.95
MR LCE posterior	0.88	0.78	0.94
MR LCE middle	0.90	0.80	0.95
MR anteroposterior center edge	0.86	0.74	0.93
MR AV 1	0.90	0.80	0.95
MR AV 2	0.95	0.90	0.97
MR AV 3	0.95	0.91	0.98
MR femoral neck shaft	0.74	0.54	0.86
MR Alpha Angle 12	0.85	0.72	0.92
MR Alpha Angle 1	0.84	0.70	0.92
MR Alpha Angle 2	0.75	0.54	0.87
MR Alpha Angle 3	0.77	0.58	0.88

12, 1, 2, 3, 12 o'clock, 1 o'clock, 2 o'clock, 3 o'clock; AV, acetabular version; CI, confidence interval; ICC, intraclass correlation coefficient; LCE, lateral center-edge;

The study validates that 3DMR reconstructions can be used to produce similar results without radiation exposure in these young patients in both types of symptomatic adult conditions of FAI and HD. 3DMR requires addition of 4–7 min of scanning time but allows similar bony assessment, evaluation of morphologic diagnosis, and produces isotropic multiplanar high-resolution soft tissue images. High-resolution MR imaging is the known gold standard for the internal derangement soft tissue findings affecting the labrum, cartilage, synovium and ligaments. We did not compare the soft tissue findings on 2DMR vs 3DMR as that was not the intent of the study. But, with high resolution imaging, 3DMR has the potential to replace routine MR and 3DCT imaging.

The quality of reconstructions from both 3DCT and 3DMR did not significantly affect the diagnostic assessment of the readers, supported by good to excellent intermodality agreements between 3DCT and 3DMR (kappa: 0.62–0.93). While 3DMR takes longer than 3DCT, we did not encounter significant

Table 4. ICC values for comparison of CT vs MR for Reader 1 and Reader 2

	Reader 1			Reader 2		
	ICC	95%CI		ICC	95%CI	
LCE anterior	0.84	0.70	0.92	0.76	0.57	0.87
LCE posterior	0.75	0.54	0.87	0.72	0.50	0.85
LCE center	0.79	0.61	0.89	0.84	0.71	0.92
Anteroposterior center edge	0.70	0.48	0.84	0.76	0.57	0.87
AV 1	0.75	0.54	0.87	0.79	0.62	0.89
AV 2	0.79	0.62	0.89	0.78	0.59	0.88
AV 3	0.75	0.56	0.87	0.72	0.51	0.85
Femoral neck shaft	0.52	0.18	0.74	0.56	0.21	0.77
Alpha Angle 12	0.71	0.47	0.85	0.82	0.67	0.91
Alpha Angle 1	0.76	0.39	0.89	0.83	0.66	0.92
Alpha Angle 2	0.74	0.53	0.86	0.71	0.49	0.85
Alpha Angle 3	0.57	0.30	0.76	0.74	0.54	0.86

2, 1, 2, 3, 12 o'clock, 1 o'clock, 2 o'clock, 3 o'clock; AV, acetabular version; ICC, intraclass correlation coefficient; CI, confidence interval; ICC, intraclass correlation coefficient; LCE, lateral center-edge.

motion artifacts. For all three readers, the qualitative diagnosis based on both 3DCT and 3DMR reconstructions showed good to excellent agreements to the final diagnosis (average PABAK: 0.80 on CT and 0.72 on MR). Previous literature has shown that

3DMR can offer exquisite detail of cartilage in both hip and knee joints and can produce 3D reconstructions.^{11,17,26,27} One study demonstrated that the geometric accuracy of 3DMR was comparable to that of 3DCT models as previously shown for the femurs of five cadaver ovine limbs imaged with both modalities.²⁸ Like the other papers that discuss 3DMR, we had similar limitations in that 3DMR took about 20–30min to create volume rendered images whereas 3DCT reconstructions took about 5 min. This is partly related to lack of fully automated and MR-dedicated software and the fact that these reconstructions are performed using a semi-automated method.

For the quantitative analysis, there was good to excellent inter-reader reliability for the measurements among all angles between two student readers on both CT and MR. There was good to excellent intermodality reliability for the majority of measurements for both student readers with the notable exception being femoral neck-shaft angle (R1 ICC: 0.52; R2 ICC: 0.56). This is explained by the fact that due to acquisition time limitations and smaller field of view used for 3D volume MR scans, the femoral shaft and small distal portion of the trochanters were not prospectively included in the imaging in some cases. In future, with advancements in the pipeline, such as compressed sensing and faster multi segmented read-out schemes, it is likely that larger 3DMR volumes can be obtained in acceptable time periods of 5min and this limitation can be overcome.

In this study, as expected, on both 3DCT and 3DMR, the LCE angle and AA were significantly different between patients with hip dysplasia and patients with FAI cam type deformity [32].

Figure 3. 3D reconstruction of hip dysplasia from 3DCT (a), left to right, and corresponding 3DMR (b), left to right.

Figure 4. 3D reconstruction of femoroacetabular impingement, cam subtype, from 3DCT (a), left to right, and corresponding 3DMR (b), left to right.

Patients with hip dysplasia had significantly lower LCE angle than the patients with cam deformity (16 degrees vs 24 degrees on CT, and 18 degrees vs 25 degrees on MR, respectively). A

cutoff for the LCE angle in hip dysplasia is 20 degrees, as used by many studies in the literature.²⁹⁻³¹ Patients with hip dysplasia had a significantly lower AA on both CT and MR than the

Figure 5. Box plots comparing the means of lateral center-edge angles (a) and alpha angles (b) between hip dysplasia and cam deformity on both CT and MR. Alpha Angle 0 is alpha angle at 12 o'clock. Asterisk signifies statistical significance $p < 0.05$.

Figure 6. Bland-Altman plots of the lateral center-edge angles (a) and the alpha angles (b) in patients with HD and FAI. Alpha Angle 0 is alpha angle at 12 o'clock.

patients with cam-type FAI (57 degrees vs 70 degrees on CT, and 60 degrees vs 70 degrees on MR, taken at 12 o'clock, respectively).

Some limitations of this study include its retrospective nature and lack of controls in this study, but it is not ethical to radiate asymptomatic individuals, and the primary intent was 3DCT vs 3DMR comparison in different disease states rather than a case-control comparison. The 3D reconstruction software used in the current evaluation is better suited for 3DCT reconstructions, and there is expected some variability in the 3DMR reconstructions due to the manual semi-automated segmentations involved. In addition, the time and effort needed for 3DMR reconstructions is not practical for every patient till dedicated MR processing algorithms become available. Currently, many institutions also do not perform 3DMR routinely, which can limit the potential for generalization. Our results were obtained from both 1.5T and 3T scanners with similar isotropic voxels and thus, this technology

can be exploited in most places doing hip preservation imaging. Finally, FAI and HD are multifactorial diagnoses. In this study, the final diagnosis was based on clinician history, physical examination, and imaging.

In the future, we hope to see fully automated and MR dedicated software for 3DMR reconstructions. There is a significant need for this technology given the demand for the pre-operative imaging for adult hip conservation surgery. We hope that there will be artificial intelligence approaches that can assist in various measurements on 3DMR with even better reliability and diagnostic capabilities.

In conclusion, 3DMR offers similar angular measurements and diagnostic capabilities as 3DCT in adult painful hip conditions with good to excellent inter-reader and intermodality agreements and can assist in pre-operative planning for hip preservation.

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