European Radiology (2019) 29:3431–3440
https://doi.org/10.1007/s00330-018-5968-z

MUSCULOSKELETAL

Cam-type femoroacetabular impingement—correlations between alpha angle versus volumetric measurements and surgical findings

Riham Dessouky[1] · Avneesh Chhabra[2,3] · Lihua Zhang[2] · Adam Gleason[2] · Rajiv Chopra[2,4] · Yonatan Chatzinoff[2] · Nicholas P. Fey[5,6] · Yin Xi[2] · Joel Wells[3]

Received: 27 July 2018 / Revised: 23 November 2018 / Accepted: 12 December 2018 / Published online: 11 February 2019

Abstract

Aim Determine correlations of 3DCT cam-type femoroacetabular impingement (FAI) measurements with surgical findings of labral tear and cartilage loss.

Methods Digital search of symptomatic cam-type FAI from July 2013 to August 2016 yielded 43 patients. Two readers calculated volumes of femoral head, bump, and alpha angles on 3DCT images. Correlations between CT and surgical findings, inter-, and intra-reader reliabilities were assessed using Spearman rank correlation and intraclass correlation coefficients (ICC).

Results Thirteen men and 14 women aged 37 ± 10 (mean ± SD) years were included. Most common clinical finding was positive flexion–adduction–internal rotation (70.4%). Twenty-seven labral tears and 20 cartilage defects were surgically detected. Significant correlations existed between femoral bump, head volumes, and extent of the labral tear ($p = 0.008$ and 0.003). No significant correlations were found between the alpha angles at 12 to 3 o'clock and the extent of labral tear ($p = 0.2$, 0.8, 0.9, and 0.09) or any measurement with the cartilage loss (p values for alpha 12 to 3, bump, and head volumes = 0.7, 0.3, 0.9, 0.9, 0.07, and 0.2). Inter- and intra-reader reliabilities were excellent to moderate for femoral head and bump volumes (ICC = 0.85, 0.52, and 0.8, 0.5) and moderate to poor for alpha angles (ICC = 0.48, 0.40, 0.05, 0.25 and 0.3, 0.24, 0.29, 0.49).

Conclusion Three dimensional volumetric measurements of cam-type FAI significantly correlate with the extent of intraoperative labral tears. Superior inter- and intra-reader reliability to that of alpha angles renders it a more clinically relevant measurement for quantifying cam morphology.

Key Points

- *The 3DCT bump volume and femoral head volume showed significant correlations with the extent of labral tear (p values = 0.008 and 0.003).*
- *No significant correlations were seen between alpha angles and the extent of labral tear (p values > 0.05).*
- *Inter- and intra-reader reliability was excellent to moderate (ICC = 0.85 and 0.52, 0.8, and 0.5) for femoral head and bump volumes while inter- and intra-reader reliability was fair to poor (ICC = 0.48, 0.40, 0.05, 0.25 and 0.3, 0.24, 0.29, 0.49) for alpha angles.*

Keywords Hip joint · Femoroacetabular impingement · Image processing · Computer-assisted · Tomography

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00330-018-5968-z) contains supplementary material, which is available to authorized users.

✉ Joel Wells
Joel.Wells@utsouthwestern.edu

[1] Department of Radiology, Zagazig University Hospitals and Faculty of Medicine, Zagazig University, Koliat Al Tob Street, Zagazig 44519, Egypt

[2] Department of Radiology, University of Texas Southwestern Medical Center, Dallas, TX, USA

[3] Department of Orthopedic Surgery, University of Texas Southwestern Medical Center, Dallas, TX, USA

[4] Advanced Imaging Research Center, University of Texas Southwestern Medical Center, Dallas, TX, USA

[5] Departments of Bioengineering and Mechanical Engineering, The University of Texas at Dallas, Richardson, TX, USA

[6] Department of Physical Medicine and Rehabilitation, University of Texas Southwestern Medical Center, Dallas, TX, USA

Abbreviations

3DCT	Three-dimensional computed tomography
FABER	Flexion-abduction-external rotation
FADIR	Flexion-adduction-internal rotation
FAI	Femoroacetabular impingement

Introduction

Femoroacetabular impingement (FAI) is a common cause of hip pain and a predisposing factor for early osteoarthrosis. It can be a result of acetabular overcoverage or malrotation [1, 2], lack of femoral head–neck offset [3, 4], and/or both. In cam-type FAI, there is a lack of normal offset at the femoral head–neck junction, which is usually located on its anterosuperior and anterolateral surfaces. Repeated contact of the femoral head–neck junction with the acetabulum results in labral shearing and delamination of cartilage from the subchondral bone [5, 6]. The most common location of soft tissue damage is observed along the anterosuperior rim of the acetabulum where the cam bump impacts. Clinically, the patients usually experience groin pain, limited internal rotation, and have a positive anterior impingement test [7, 8].

3D computed tomography (3DCT) has been used as an accurate tool to assess femoral head–neck junction bone anatomy and can be easily post-processed using a commercially available software to generate volume-rendered and radial images for the angular measurements. Alpha angle measurements on radial 3DCT imaging are also sensitive in quantifying the femoral head–neck offset and capture the deformity better than the routinely used radiographs with moderate inter-reader reliability [9]. Furthermore, 3DCT measurements aid in preoperative planning and correlate with intraoperative findings [10]. Segmentation and volumetric measurements can also be obtained using the same 3DCT data due to the differences in the density of the developmental bump (cam lesion) and the native femoral head [11, 12]. To date, there is insufficient data regarding correlations of the extent of labral or cartilage damage with the degree of alpha angles and femoral head volume and/or bump volume.

The aim of this study was to obtain correlations of radial 3DCT-generated alpha angles and segmented volumes of the femoral head and bump with surgical findings of the extent of labral tears and cartilage loss. We hypothesised that 3DCT cam measurements can determine the extent of intra-articular soft tissue damage on surgery. As a secondary aim, inter- and intra-reader reliabilities were assessed for both alpha angles and volumetric FAI measurements.

Methods

Study population

This was a retrospective, cross-sectional evaluation performed in compliance with the Institutional Review Board requirements, following the Health Insurance Portability and Accountability Act. Chart reviews were performed for all clinically symptomatic FAI patients referred from the Sports Medicine Clinic for preoperative 3DCT planning and arthroscopic surgery from July 2013 to August 2016. Institutional database search yielded a consecutive series of 43 patients. Anteroposterior (A-P), Dunn view radiographs, and 3DCTs were obtained in all patients as a part of standard care. Inclusion criteria were: adult patients presenting with hip and/or groin pain, clinical criteria of FAI, and radiological findings of cam (aspherical femoral head with formation of a bump at the head and neck junction, alpha angle > 55° on the Dunn view) or mixed cam and pincer FAI (cam with acetabular retroversion or overcoverage (as determined by lateral centre edge angle > 40°)) Exclusion criteria were: previous history of surgery on the symptomatic side or isolated pincer FAI (Fig. 1). Patients were operated on at our institute, and all surgical findings were recorded.

Clinical findings

As a part of their clinical care, standard clinical examination was performed by an experienced orthopaedic sports surgeon for all patients. This included tests for range of motion (hip flexion, internal and external rotation, straight leg raising test, flexion-adduction-internal rotation (FADIR), and flexion-abduction-external rotation (FABER), muscle strength, and sensation. Clinical criteria for evaluation of cam FAI were: limited passive hip flexion (≤ 105), limited internal rotation at 90° of hip flexion (≤ 15), and positive anterior impingement test on FADIR [7]. Clinical findings were recorded for all patients included in the study.

CT examination and analysis

Image acquisition 3DCT scans were uniformly acquired on two multidetector CT scanners (Optima CT 600, GE Healthcare and Aquilion 64, Canon Medical Systems) from the upper border of L5 vertebra to the proximal femoral metadiaphysis using the following parameters: beam collimation (64 × 0.625 mm), tube voltage (120 kVp), and tube current (140–280 mAs). Both soft tissue and bone reconstruction kernels were sent to picture archiving and communication system (PACS). The soft tissue kernel was imported into an independent reconstruction software (Tera Recon, Intuition) for further image processing.

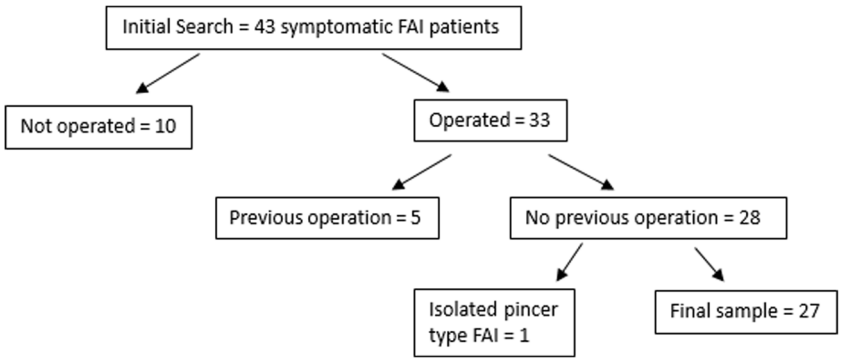

Fig. 1 Flow chart outlining the patient selection

Image post processing and analysis Images were reviewed by two independent readers (a second-year radiology resident and a radiologist with 8 years of experience) following training on a separate set of 3DCT images prior to the blinded review. Radial reconstructions of the femoral head and neck were performed using the methods previously described by Nepple et al and Arezoomand et al [13, 14]. Using a best-fit circle to define the femoral head contour, alpha angles were measured between the bisection of the femoral neck axis with a line connecting the centre of the femoral head to the point of beginning of asphericity, as described by Nötzli et al [15, 16]. To standardise the measurements between both readers, alpha angles were measured at four pre-defined clock positions (12, 1, 2, and 3 o'clocks) on the coronal images by rotating the vertical cursor to each of the corresponding clock positions on the axial clock face image. The 12 o'clock position was cranial and 3 o'clock position was anterior for both hips (Figs. 2 and 3). Cam FAI was defined as alpha angles exceeding 55°.

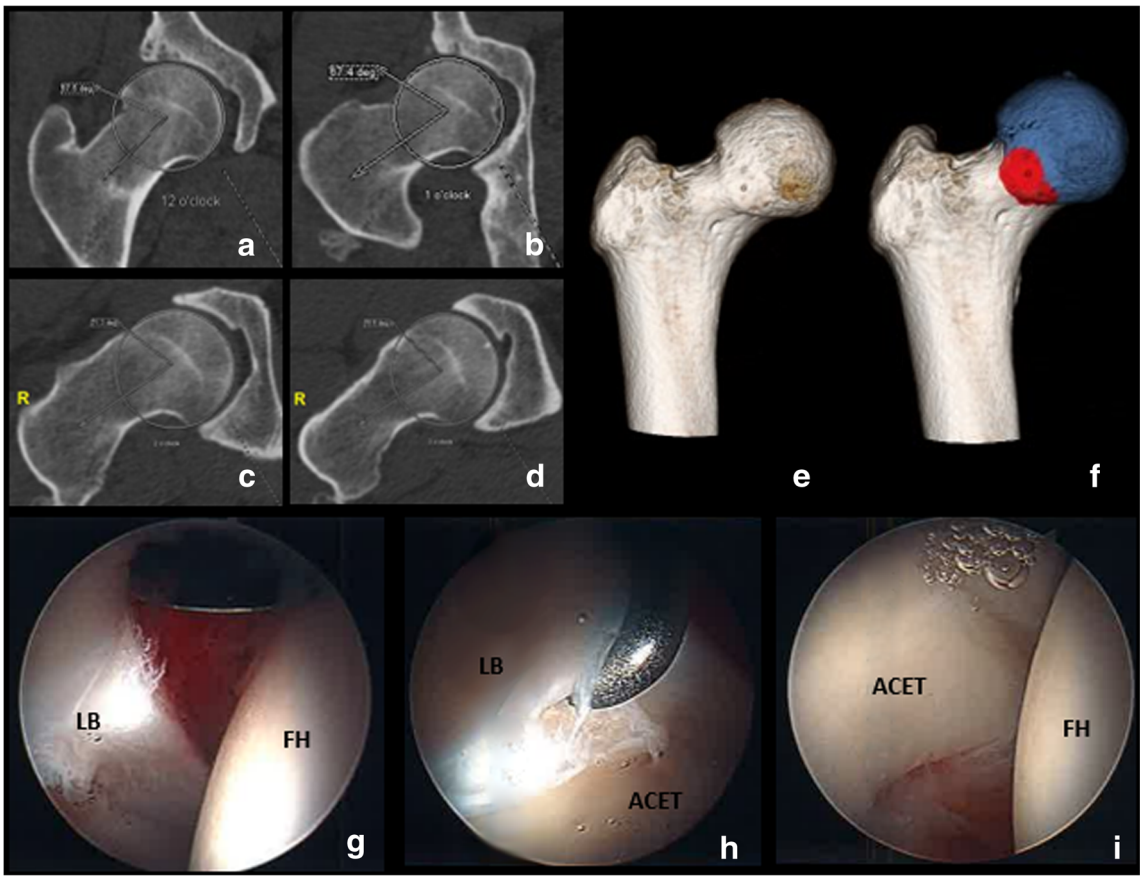

Fig. 2 29-year-old male hockey player with right hip pain. During clinical examination, a full range of motion with negative FABER and FADIR was observed. Radial 3DCT images (**a, b, c**, and **d**) show alpha angle measurements of 67.5, 67.4, 71.3, and 75.5 at 12, 1, 2, and 3 o'clock positions. Volumetric measurements (**e** and **f**) show femoral head and bump volumes of 51.3 and 4.35 cm^3, respectively. Upon surgery, the extent of the labral tear was from 12:30 to 2:30 o'clock position (**h**). Acetabular cartilage (ACET) had partial-thickness cartilage loss. Femoral head cartilage (FH) was intact (**i**)

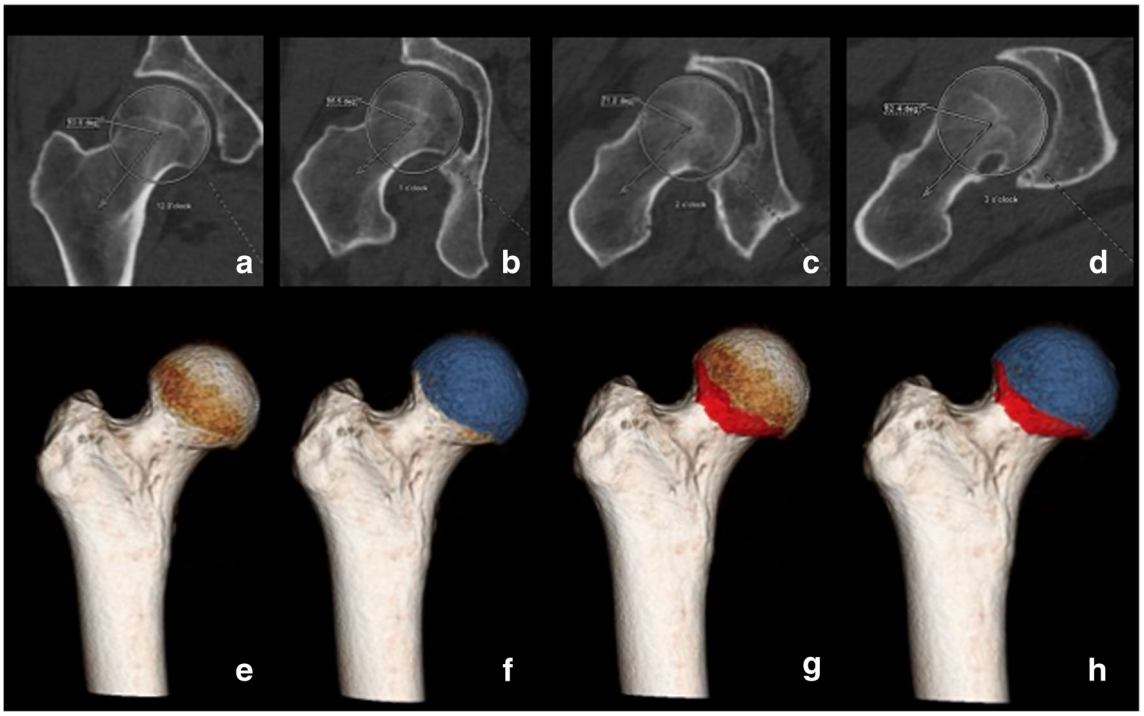

Fig. 3 42-year-old female non-athlete with hip and groin pain. During clinical examination, she had mild restricted internal rotation with no pain on FABER or FADIR. Radial 3DCT images (**a** to **d**) show alpha angle measurements of 61.1, 68.1, 72.1, and 66.2 at 12, 1, 2, and 3 o'clock positions, respectively. Volumetric measurements (**e** to **h**) show femoral head (blue) and bump (red) volumes of 35.6 and 3.33 cm^3, respectively

This cutoff value was chosen to reduce overlap with variations in alpha angles among the general population [16–18], thus reducing false positive findings of FAI. Lateral centre edge angle (LCEA) was also measured [19], and patients with isolated pincer FAI (LCEA > 40° with normal alpha angle measurements) were excluded from the final sample.

Using the same software, 3D volume-rendered images of the pelvis were obtained. After semi-automated segmentation of the femur using a free-hand ROI, a region-grow thresholding colour tool was used to separately segment the femoral head and respective cam lesion with automatic calculation of their volumes (Fig. 4). Osteoarthritis grade was recorded for each hip on AP pelvis radiographs by the surgeon as per Tönnis grading system [20]. The Tönnis classification of osteoarthritis is graded as 0 (no changes), 1 (widened sclerotic sourcil with minimal osteophyte formation), 2 (moderate loss of joint space and cyst formation), and 3 (< 1 mm of joint space, large cystic changes, or no joint space). The alpha angles were obtained from the Dunn views (corresponding to 1 and 2 o'clock position on radial CTs) by the senior reader. Radial CT and volumetric measurements were also repeated by the second reader, 6 months after the first read.

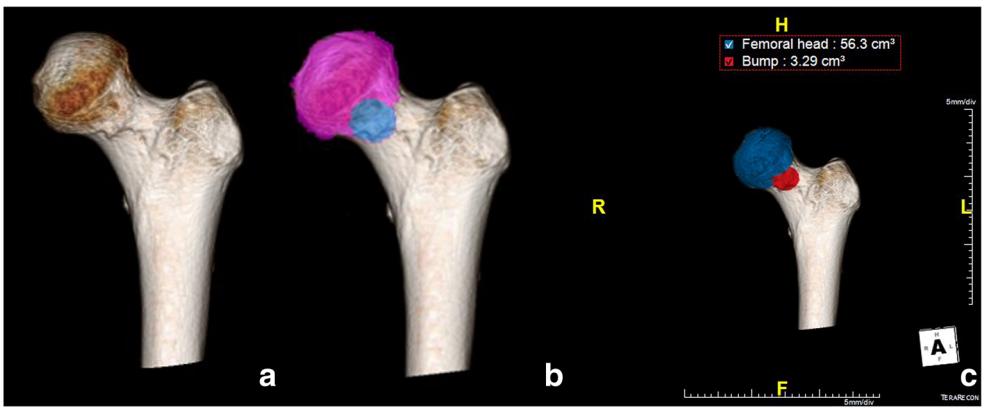

Fig. 4 3D volume-rendered images (**a**) showing use of region growing tool (**b**) followed by colour mask (**c**) to automatically calculate femoral head and bump volume

Surgical findings

Twenty-seven hips in 27 patients were operated upon by the same surgeon who performed the clinical evaluation. All operative reports included labral, femoral, and acetabular cartilage findings. To avoid bias in interpretation of surgical findings, all labral cartilage findings and preoperative radiographs were re-evaluated by a second surgeon specialised in sports surgery. To avoid variability in the interpretation of labral tear locations in right versus left hips, the labral tears were described using predetermined clock positions as validated in the literature [21, 22]. Cartilage defects were described as partial-thickness cartilage loss (Outerbridge grades 1 to 3) or full-thickness cartilage loss (grade 4).

Data collection and statistical analysis

Patient demographics and clinical data, alpha angle and volumetric femoral head and bump measurements on 3DCT, Tönnis grades and alpha angles on x-rays, and extent of labral tear and cartilage loss on surgery were recorded in a spreadsheet (Excel 2010, Microsoft). Descriptive statistics were used to summarise patient demographic and clinical findings, radiographic Tönnis grades and alpha angles, 3DCT measures, and surgical findings. Spearman rank correlations were used to find associations between mean volumetric and alpha angle measurements on 3DCT and the extent of labral tear and cartilage loss on surgery. Fisher's z-transformation was used to calculate 95% confidence intervals (CI). Intraclass correlation coefficients (ICC) were used to assess inter- and intra-reader agreements. Any p value < 0.05 was considered statistically significant.

Results

Study population and clinical findings

Twenty-seven 3DCTs of the hips in 27 patients (13 males and 14 females) constituted the final sample. Mean and standard deviation (SD) of age was 37 ± 10 years. All patients had unilateral hip pain on presentation, of which 14 were right and 13 were left (1.08:1). Upon clinical examination, 19 patients had positive anterior impingement on FADIR, 15 had limited flexion, and 8 had limited internal rotation (Table 1).

Imaging findings

Alpha angles Alpha angles were recorded in 27 hips for 27 patients using radial 3DCT imaging at the 12, 1, 2, and 3 o'clock positions. Mean and SD of alpha angles at 12, 1, 2, and 3 o'clock were 54.1 ± 13.4, 59.3 ± 13.8, 59 ± 14.7, and 54.3 ± 15.8°, respectively.

Volumetric measures Volumetric measures of femoral head and bump were recorded in all 27 hips using volume-rendered 3DCT images. It took approximately 20 min to record both alpha angles and volumes. Volume measurements alone took less than 5 min (3.9 ± 1.7 min, mean ± SD) (Fig. 5). Mean head volume was 49.7 ± 11.5 cm^3 and mean bump volume was 4.6 ± 2.6 cm^3.

Radiographic Tönnis grades and alpha angles A-P radiographs and Dunn views were used for preoperative evaluation of all symptomatic hips. Tönnis grades were used to exclude osteoarthritic hips on A-P radiographs. Mean Tönnis grade was 0.93 ± 0.7 (Supplementary Table 1). Mean alpha angles measured on Dunn views were 61 ± 5° (mean ± SD).

Surgical findings

Labral findings All 27 patients had labral tears. To statistically analyse the extent of the labral tear, the number of clock hours was converted into a single number, i.e. labral tear extending from 12 to 2 o'clock was recorded as 2 h and 12 to 2:30 o'clock labral tear was recorded as 2.5 h. Mean labral tear extent was 1.5 ± 0.99 h.

Cartilage findings Twenty cartilage defects were described in 27 hips on surgery (16 on the acetabular, 1 on the femoral, and 3 on both acetabular and femoral cartilages). The ratio of acetabular and femoral cartilage loss was approximately 5:1. Similar frequency of partial and full-thickness cartilage defects were found on the acetabular side (Table 2).

Table 1 Distribution of clinical symptoms among patient population ($n = 27$)

Clinical criteria	Frequency (n)	Percentage of patients (%)
Limited passive hip flexion	15	15/27 (55.6)
Limited internal rotation	8	8/27 (29.6)
Positive anterior impingement test	19	19/27 (70.4)

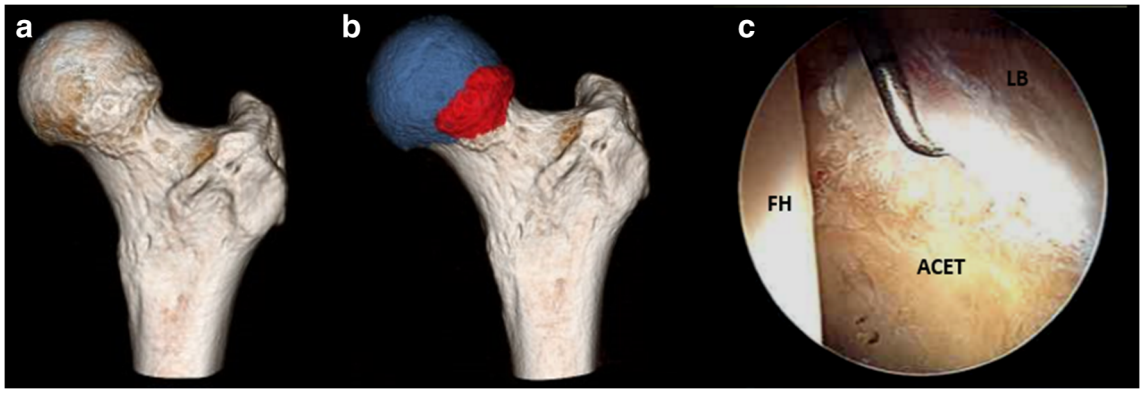

Fig. 5 46-year-old non-athletic male with left groin pain. During clinical examination, he had limited internal rotation on the left side with positive FABER and FADIR. Volumetric CT measurements (**a** and **b**) show femoral head (blue) and bump (red) volumes of 70.6 and 8.68 cm^3, respectively. Upon surgery (**c**), the extent of the labral tear was from 1:30 to 3:30 o'clock position (H). Acetabulum (ACET) had some cartilage wear. Femoral head cartilage (FH) was intact

Correlations between imaging and surgical findings

On 3DCT, alpha angles at 12, 1, 2, and 3 o'clocks did not correlate with the extent of labral tear on surgery. Spearman correlations were − 0.3, 0.05, − 0.02, and 0.36 with CI − 0.63 to 0.13, − 0.36 to 0.44, − 0.42 to 0.39, and − 0.07 to 0.67, respectively. The *p* values were 0.2, 0.8, 0.9, and 0.09, respectively. Femoral bump and head volumes significantly correlated with the extent of labral tear on surgery. Spearman correlations were 0.50 and 0.55 with CI 0.13–0.73 and 0.20–0.76, respectively. The *p* values were 0.008 and 0.003, respectively (Table 3, Fig. 6). There were no correlations between alpha angles or volumes and articular cartilage damage. The *p* values were 0.67, 0.29, 0.86, 0.87 and 0.07, 0.12, 0.46, respectively (Table 3). Upon comparing radiographic alpha angle measurements, there were no significant correlations with the extent of the labral tears (Spearman correlation = 0.28, *p* value = 0.17) or cartilage damage (Spearman correlation = 0.21, *p* = 0.11).

Reader agreements

Inter-reader agreement was classified as excellent (> 0.80), good (0.61–0.80), moderate (0.41–0.60), fair (0.20–0.40), and poor (< 0.20) using 95% CI. Femoral volumetric measurements showed excellent and moderate inter-reader agreements (ICC = 0.85 and 0.52) for the head and bump volumes, respectively. Alpha angles at 12, 1, 2, and 3 o'clock showed moderate and poor inter-reader agreements (ICC = 0.48, 0.40, 0.05, and 0.25, respectively) (Table 4). Intra-reader agreement was moderate to excellent for volumetric (ICC = 0.46 and 0.80) and fair to moderate for the alpha angle measurements (ICC = 0.24 to 0.49) (Table 5).

Discussion

Symptomatic FAI has an important association with premature osteoarthritis (OA) of the hip. From the surgical stand point, a decision to preserve or replace the hip is based on a combination of careful history taking, clinical examination, and preoperative imaging. The aim of imaging is to recognise the morphology of osseous abnormalities and characterise the extent of chondrolabral damage as accurately as possible [23]. Recent literature has discussed cutoff values for alpha angle, 3DCT radial imaging to quantify cam lesions [11, 23, 24], and MRI grading systems to evaluate the extent of labral and cartilage damage in FAI [25], but, to the best of our knowledge, no study has correlated 3DCT measurements with the extent of the surgical findings.

This study highlights an innovative new way of evaluating cam volume measurement. We found that cam and

Table 2 Articular cartilage findings after surgery

Cartilage findings (from a total of 27 patients)	Acetabular		Femoral	
	Frequency (*n*)	Percentage (%)	Frequency (*n*)	Percentage (%)
Full-thickness cartilage defect	9	33	1	4
Partial-thickness cartilage defect	10	37	3	11
Total (*n*/%)	19	70	4	15

Table 3 Correlations of 3D volumetric and alpha angles measurements with surgical findings of labral tear and cartilage loss. Last column represents false discovery rate (FDR), adjusted *p* values for cartilage loss, and labral tear in clock hours, respectively

Surgical findings	3DCT measurement	Spearman correlation	95% confidence interval (Fisher's *z*-Transformation)		*p* value	FDR adjusted *p* value
Cartilage loss	Alpha angle 12 o'clock	0.11	−0.38	0.55	0.67	0.87
	Alpha angle 1 o'clock	−0.26	−0.63	0.23	0.29	0.67
	Alpha angle 2 o'clock	0.04	−0.42	0.49	0.86	0.87
	Alpha angle 3 o'clock	0.04	−0.43	0.50	0.87	0.87
	Bump volume	0.35	−0.04	0.64	0.07	0.41
	Femoral head volume	0.31	−0.09	0.61	0.12	0.41
	Head/bump ratio	0.15	−0.25	0.50	0.46	0.80
Labral tear/clock hours	Alpha angle 12 o'clock	−0.30	−0.6	0.13	0.16	0.22
	Alpha angle 1 o'clock	0.05	−0.36	0.44	0.83	0.93
	Alpha angle 2 o'clock	−0.02	−0.42	0.39	0.93	0.93
	Alpha angle 3 o'clock	0.36	−0.07	0.67	0.09	0.16
	Bump volume	0.50	0.13	0.73	0.008*	0.03
	Femoral head volume	0.55	0.20	0.76	0.003*	0.02
	Head/bump ratio	0.3	−0.05	0.63	0.08	0.16

*Statistically significant correlations

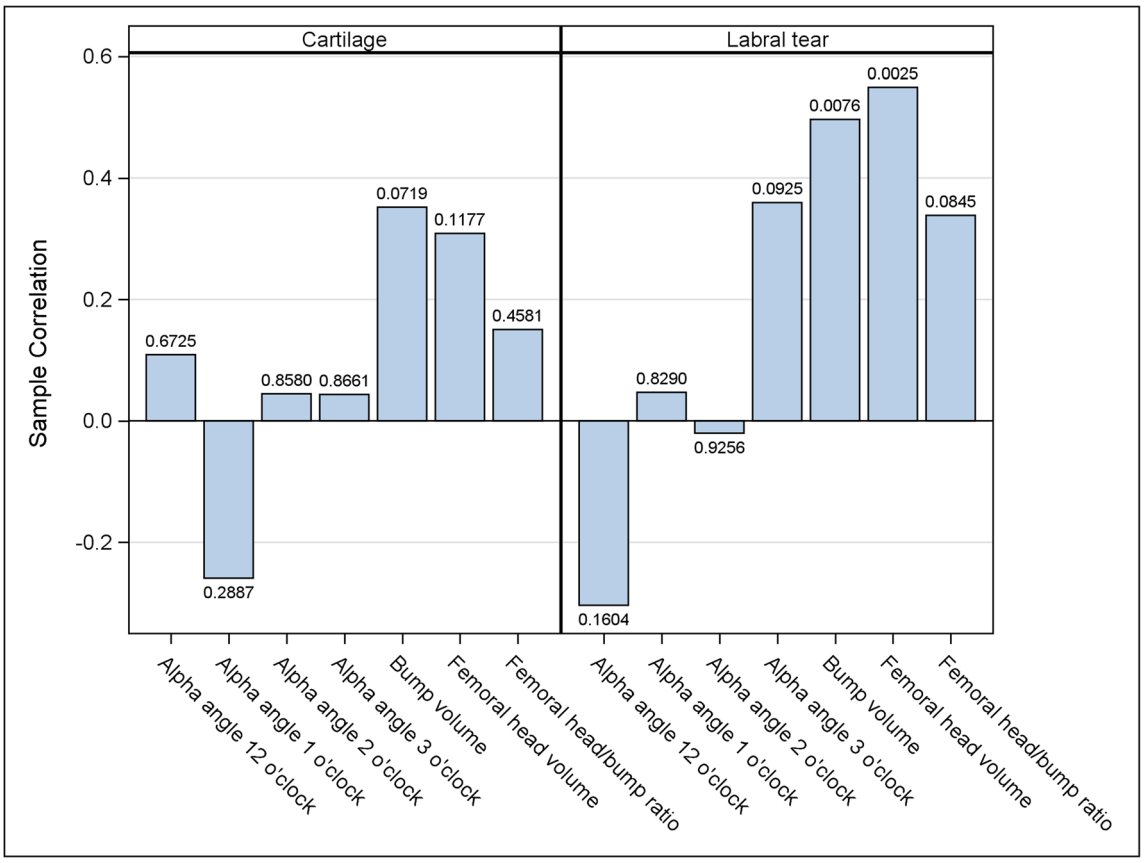

Fig. 6 Bar chart for Spearman correlations for various 3DCT measurements with surgical findings of labral tear and cartilage loss. Height of each column represents correlation and numbers represent *p* values for each parameter as determined by Spearman's correlation coefficient

Table 4 Inter-reader agreement for alpha angles and femoral head and bump volumes

3DCT measurement	Intraclass correlation coefficient (ICC)	95% confidence interval (CI)	
Alpha angle 12 o'clock	0.48	0.13	0.73
Alpha angle 1 o'clock	0.40	0.00	0.69
Alpha angle 2 o'clock	0.05	− 0.36	0.44
Alpha angle 3 o'clock	0.25	0.15	0.57
Bump volume	0.52	0.15	0.76
Femoral head volume	0.85	0.69	0.93

femoral head segmentations are much faster and more reliable when compared to the alpha angle measurements. Furthermore, our data showed significant positive correlations between femoral head and bump volumes and the extent of labral tear. This agreed with a previous study showing that labral tears occurs 3.6 times more often in patients with a radiographically abnormal femoral head–neck offset [26]. Alpha angles did not correlate with the extent of labral tear. This agrees with previous studies showing overlap in FAI-associated alpha angle measurements among asymptomatic hips [16, 27, 28], variability in alpha angles on MR imaging [28–30], and a recent study by Smith et al showing significant variability in alpha angle measurements on x-ray, CT, and MRI [31]. We also found moderate to poor inter-reader reliability for alpha angle measurements. This was lower than the previously described findings by Beaulé et al [9].

Other important findings included predominance of positive anterior impingement on FADIR in cam FAI patients (70.4%) and high percentage of patients (70%) with acetabular cartilage loss on surgery. This is expected and agrees with previous studies associating a positive anterior impingement test [32] and cartilage wear with FAI impingement [25, 33]. The 3D volume-rendered and segmented reconstructions are now routine in our practice as the referring expert surgeons require it for preoperative planning. It provides them a sense of the extent of the bump qualitatively, increases the confidence of preoperative diagnosis, and better estimates the amount of required femoroplasty. It remains to be seen if the routine use of such imaging would result in more adequate bump resections and less recurrence of future symptoms from residual FAI.

Despite the encouraging findings, this study had several limitations. Retrospective analysis of a specific group of patients referred from sports medicine clinic and an even lower number of patients undergoing surgery results in selection bias. However, we made sure that the series of patients were consecutive and that another surgeon evaluated the intraoperative photos, blinded to the 3DCT measurements. Furthermore, clinical assessments were performed, but could not be correlated to the surgical findings. This was due to variable examination methods and findings. Finally, we did not evaluate the effect of the acetabular anatomy on labral and cartilage damage, nor did we evaluate the contralateral normal hips. This was not possible due to previously operated contralateral hips in some patients which could not be compared to the asymptomatic, unoperated hips.

This study initially aimed to test a new, simplified, quantitative 3DCT method for cam quantification that could be applied in the rapid workflow of clinical practice and at the same time correlate well with surgical findings. Future studies should be aimed at validating 3DCT volumetric measures in larger surgical cohorts to confirm correlations and compare differences to the asymptomatic hips and controls.

Table 5 Intra-reader agreement for alpha angles and femoral head and bump volumes

3DCT measurement	Intraclass correlation coefficient (ICC)	95% confidence interval (CI)	
Alpha angle 12 o'clock	0.3	− 0.1	0.61
Alpha angle 1 o'clock	0.24	− 0.15	0.57
Alpha angle 2 o'clock	0.29	− 0.1	0.61
Alpha angle 3 o'clock	0.49	0.14	0.74
Bump volume	0.46	0.1	0.71
Volume of femoral head	0.8	0.62	0.91
Head/bump ratio	0.14	− 0.24	0.49

Conclusion

3D volumetric measurements of cam-type FAI significantly correlate with the extent of intraoperative labral tear with superior inter- and intra-reader reliability than the alpha angle, rendering it a more clinically relevant method to quantify cam morphology.

Funding The authors state that this work has not received any funding.

Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Avneesh Chhabra, MD.

Conflict of interest The authors of this manuscript declare relationships with the following companies:

RD, LZ, AG, RC, YC, NPF: no conflicts of interest.

AC: consultant ICON Medical, royalties: Jaypee, Wolters (not related).

Statistics and biometry One of the authors has significant statistical expertise.

Informed consent Written informed consent was waived by the Institutional Review Board.

Ethical approval Institutional Review Board approval was obtained.

Methodology
- retrospective
- cross-sectional study
- performed at one institution

References

1. Siebenrock KA, Schoeniger R, Ganz R (2003) Anterior femoroacetabular impingement due to acetabular retroversion. Treatment with periacetabular osteotomy. J Bone Joint Surg Am 85:278–286. https://doi.org/10.2106/00004623-200302000-00015
2. Reynolds D, Lucas J, Klaue K (1999) Retroversion of the acetabulum. A cause of hip pain. J Bone Joint Surg Br 81:281–288. https://doi.org/10.1302/0301-620X.81B2.8291
3. Eijer H, Leunig M, Mahomed MN, Ganz R (2001) Cross-table lateral radiographs for screening of anterior femoral head-neck offset in patients with femoro-acetabular impingement. Hip Int 11:37–41. https://doi.org/10.1177/112070000101100104
4. Ito K, Minka MA 2nd, Leunig M, Werlen S, Ganz R (2001) Femoroacetabular impingement and the cam-effect. A MRI-based quantitative anatomical study of the femoral head-neck offset. J Bone Joint Surg Br 83:171–176. https://doi.org/10.1302/0301-620X.83B2.11092
5. Carter DR, Vasu R, Harris WH (1982) Stress distributions in the acetabular region-II. Effects of cement thickness and metal backing of the total hip acetabular component. J Biomech 15:165–170. https://doi.org/10.1016/0021-9290(82)90248-2
6. Leunig M, Casillas MM, Hamlet M et al (2000) Slipped capital femoral epiphysis: early mechanical damage to the acetabular cartilage by prominent femoral metaphysis. Acta Orthop Scand 71:370–375
7. Clohisy JC, Beaulé PE, O'Malley A, Safran MR, Schoenecker P (2008) AOA symposium. Hip disease in the young adult: current concepts of etiology and surgical treatment. J Bone Joint Surg Am 90:2267–2281. https://doi.org/10.2106/JBJS.G.01267
8. Clohisy JC, Knaus ER, Hunt DM, Lesher JM, Harris-Hayes M, Prather H (2009) Clinical presentation of patients with symptomatic anterior hip impingement. Clin Orthop Relat Res 467:638–644. https://doi.org/10.1007/s11999-008-0680-y
9. Beaulé PE, Zaragoza E, Motamedi K, Copelan N, Dorey FJ (2005) Three-dimensional computed tomography of the hip in the assessment of femoroacetabular impingement. J Orthop Res 23:1286–1292. https://doi.org/10.1016/j.orthres.2005.03.011.1100230608
10. Ross JR, Bedi A, Stone RM et al (2014) Intraoperative fluoroscopic imaging to treat cam deformities: correlation with 3-dimensional computed tomography. Am J Sports Med 42:1370–1376. https://doi.org/10.1177/0363546514529515
11. Röling MA, Visser MI, Oei EH, Pilot P, Kleinrensink GJ, Bloem RM (2015) A quantitative non-invasive assessment of femoroacetabular impingement with CT-based dynamic simulation — cadaveric validation study. BMC Musculoskelet Disord 16:50. https://doi.org/10.1186/s12891-015-0504-7
12. Speirs AD, Beaulé PE, Rakhra KS, Schweitzer ME, Frei H (2013) Bone density is higher in cam-type femoroacetabular impingement deformities compared to normal subchondral bone. Osteoarthritis Cartilage 21:1068–1073. https://doi.org/10.1016/j.joca.2013.04.016
13. Nepple JJ, Prather H, Trousdale RT et al (2013) Diagnostic imaging of femoroacetabular impingement. J Am Acad Orthop Surg 21:S20–S26. https://doi.org/10.5435/JAAOS-21-07-S20
14. Arezoomand S, Lee WS, Rakhra KS, Beaulé PE (2015) A 3D active model framework for segmentation of proximal femur in MR images. Int J Comput Assist Radiol Surg 10:55–66. https://doi.org/10.1007/s11548-014-1125-6
15. Nötzli HP, Wyss TF, Stoecklin CH, Schmid MR, Treiber K, Hodler J (2002) The contour of the femoral head-neck junction as a predictor for the risk of anterior impingement. J Bone Joint Surg Br 84–B:556–560
16. Sutter R, Dietrich TJ, Zingg PO, Pfirrmann CW (2012) How useful is the alpha angle for discriminating between symptomatic patients with cam-type femoroacetabular impingement and asymptomatic volunteers? Radiology 264:514–521. https://doi.org/10.1148/radiol.12112479
17. Wyles CC, Norambuena GA, Howe BM et al (2017) Cam deformities and limited hip range of motion are associated with early osteoarthritic changes in adolescent athletes: a prospective matched cohort study. Am J Sports Med 45:3036–3043. https://doi.org/10.1177/0363546517719460
18. Audenaert EA, Peeters I, Vigneron L, Baelde N, Pattyn C (2012) Hip morphological characteristics and range of internal rotation in femoroacetabular impingement. Am J Sports Med 40:1329–1336. https://doi.org/10.1177/0363546512441328
19. Omoumi P, Thiery C, Michoux N, Malghem J, Lecouvet FE, Vande Berg BC (2014) Anatomic features associated with femoroacetabular impingement are equally common in hips of old and young asymptomatic individuals without CT signs of osteoarthritis. AJR Am J Roentgenol 202:1078–1086. https://doi.org/10.2214/AJR.12.10083
20. Tönnis D, Heinecke A (1999) Acetabular and femoral anteversion: relationship with osteoarthritis of the hip. J Bone Joint Surg Am 81:1747–1770. https://doi.org/10.2106/JBJS.L.00710
21. Wells J, Nepple JJ, Crook K et al (2017) Femoral morphology in the dysplastic hip: three-dimensional characterizations with CT. Clin

Orthop Relat Res 475:1045–1054. https://doi.org/10.1007/s11999-016-5119-2
22. Philippon MJ, Stubbs AJ, Schenker ML, Maxwell RB, Ganz R, Leunig M (2007) Arthroscopic management of femoroacetabular impingement: osteoplasty technique and literature review. Am J Sports Med 35:1571–1580. https://doi.org/10.1177/0363546507300258
23. Bittersohl B, Hosalkar HS, Hesper T, Tiderius CJ, Zilkens C, Krauspe R (2015) Advanced imaging in femoroacetabular impingement: current state and future prospects. Front Surg 2:34. https://doi.org/10.3389/fsurg.2015.00034
24. Bouma HW, Hogervorst T, Audenaert E, Krekel P, van Kampen PM (2015) Can combining femoral and acetabular morphology parameters improve the characterization of femoroacetabular impingement? Clin Orthop Relat Res 473:1396–1403. https://doi.org/10.1007/s11999-014-4037-4
25. Neumann J, Zhang AL, Schwaiger BJ et al (2018) Validation of scoring hip osteoarthritis with MRI (SHOMRI) scores using hip arthroscopy as a standard of reference. Eur Radiol. https://doi.org/10.1007/s00330-018-5623-8
26. Peelle MW, Della Rocca GJ, Maloney WJ, Curry MC, Clohisy JC (2005) Acetabular and femoral radiographic abnormalities associated with labral tears. Clin Orthop Relat Res 441:327–333. https://doi.org/10.1097/01.blo.0000181147.86058.74
27. Kim J, Choi JA, Lee E, Lee KR (2015) Prevalence of imaging features on CT thought to be associated with femoroacetabular impingement: a retrospective analysis of 473 asymptomatic adult hip joints. AJR Am J Roentgenol 205:W100–W105. https://doi.org/10.2214/AJR.14.13130
28. Ehrmann C, Rosskopf AB, Pfirrmann CW, Sutter R (2015) Beyond the alpha angle: alternative measurements for quantifying cam-type deformities in femoroacetabular impingement. J Magn Reson Imaging 42:1024–1031. https://doi.org/10.1002/jmri.24861
29. Lohan DG, Seeger LL, Motamedi K, Hame S, Sayre J (2009) Cam-type femoral-acetabular impingement: is the alpha angle the best MR arthrography has to offer? Skeletal Radiol 38:855–862. https://doi.org/10.1007/s00256-009-0745-3
30. Magerkurth O, Jacobson JA, Jax F et al (2013) Femoroacetabular cam-type impingement: global assessment of the femoral head-neck junction on a single reformatted MR image. Radiology 268:822–830. https://doi.org/10.1148/radiol.13121961
31. Smith KM, Gerrie BJ, McCulloch PC, Lintner DM, Harris JD (2017) Comparison of MRI, CT, Dunn 45° and Dunn 90° alpha angle measurements in femoroacetabular impingement. Hip Int 284:450–455
32. Yen YM, Kocher MS (2013) Clinical and radiographic diagnosis of femoroacetabular impingement. J Pediatr Orthop 33(Suppl 1):S112–S120
33. Amanatullah DF, Antkowiak T, Pillay K et al (2015) Femoroacetabular impingement: current concepts in diagnosis and treatment. Orthopedics 38:185–199. https://doi.org/10.3928/01477447-20150305-07