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FULL PAPER

3D CT segmentation of CAM type femoroacetabular impingement—reliability and relationship of CAM lesion with anthropomorphic features

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Objective: Evaluate feasibility and reliability of 3DCT semi-automatic segmentation and volumetrics of CAM lesions in femoroacetabular impingement and determine correlations with anthropometrics.

Methods: Consecutive series of 43 patients with CAM type FAI underwent 3DCT. 20 males and 23 females (30 unilateral and 13 bilateral symptomatic hips) were included. 56 CAM lesions and femoral heads were segmented by two readers. Radial images were obtained for alpha angles. Pearson and ICC correlations were used for analysis.

Results: In 43 patients (male: female = 1 : 1.15), mean $\pm$ SD of age, height, BMI were 36.6 ± 11.47 years, 1.72 ± 0.10 meters and 26.25 ± 4.31 kg m⁻². Femoral head and bumps were segmented in 4 min. Inter reader reliability was good to excellent for volumetrics and poor for alpha

angles. Mean $\pm$ SD of CAM lesion and femoral head volumes were significantly higher (6.7 ± 2.5 cc³ and 62.9 ± 10.8 cc³) among males than females ($p < 0.001$) and with increasing patient height (Pearson correlation and p -values = 0.45, 0.0006; 0.82, < 0.0001 respectively).

Conclusion: Volumetric analysis of CAM lesion shows better inter reader reliability than alpha angle measurements. CAM and femoral head volumes exhibit significant correlations with patient heights that may aid in pre-operative planning for femoroplasty.

Advances in knowledge: Femoral head & CAM volumes are segmented three times faster than alpha angles with superior inter reader reliability than alpha angles. Femoral head & CAM volumes are significantly larger in males and positively correlate with patients' heights.

INTRODUCTION

Femoroacetabular impingement (FAI) is a common cause of hip pain and refers to a condition in which structural abnormalities of the proximal femur and/or acetabulum lead to mechanical abutment during hip motion.¹ It is classified into CAM, pincer and mixed (CAM and pincer) types and is associated with labral and cartilage injury.² The goal of surgical treatment is to correct the impingement anatomy and repair the damaged labrum and/or cartilage to prevent premature osteoarthritis. Thus, early recognition and characterization of FAI is important for pre-surgical planning. This includes defining the presence and extent of CAM lesions, which can be addressed with femoroplasty.³ However, long-term outcome studies are pending. Siebenrock et al suggested that CAM lesions are developmental and occur as a result of ossification of previous physeal injury.⁴

Recent cadaveric study has shown that femoral CAM bumps gradually developed over many decades.⁵ Cadavers have even been used in the characterization of motion limiting FAI deformities imaged using three dimensional CT (3DCT).^{5,6} With widespread use of 3DCT of pelvis,⁷ CAM lesions are commonly encountered as an asymptomatic finding, even in patients with dysplastic unstable hips.⁸ Regardless of the aetiology and conflicting reports of significance, CAM lesions exhibit higher CT bone mineral density than the native femoral head.⁹ These differences in bone mineral density can be exploited to obtain individual segmentations of femoral head and CAM lesions for the purposes of pre-surgical planning.^{10–12} Traditionally, an alpha angle greater than 50–55 degrees on hip radiograph is used to justify the diagnosis of FAI.¹³ Currently, 3DCT with radial imaging has been advocated to be the most

Figure 1. Color coded 3D volumetric segmentation of femoral head (blue) and CAM bump (red) using region growing tool.

sensitive modality in the quantification of normal and abnormal alpha angles.^{9,12,14} Recent literature has proposed using higher cut off values of 65–70 degrees to differentiate normal from FAI hips,¹⁵ with alpha angles being most pronounced at 1–2 O'clock positions (anterosuperior femoral head and neck junction). Preliminary studies have shown that male patients with FAI display a larger mean alpha angle and therefore, exhibit a more severe cam-type deformity than female patients.^{14,16} However, it is not known whether other anthropomorphic features play a role in femoroacetabular impingement. In addition, questions have been raised regarding the reliability of alpha angle measurements.¹⁷ Kang *et al* developed a method with raw DICOM data to quantify femoral CAM lesions using 3-D modeling from CT scans,¹⁸ however it requires special computer lab processing. It is standard for our hip surgeons and as shown in articles published from various institutes to obtain 3D CT for pre-operative planning and MR arthrogram for labrum.^{9,10,17,18} MR bone modeling is not yet standard or widely available due to cost and unavailable automatic segmentation software. Using a commercially available 3D segmentation software on an independent workstation, it is possible to segment and calculate separate volumes of femoral head and bump in a matter of few minutes (Figure 1).

Our aim was to evaluate the feasibility and reliability of 3DCT semi-automatic segmentation and volumetrics of CAM lesion in femoro-acetabular impingement patients and to determine their correlation with anthropomorphic features. We hypothesized that bone segmentation and volumetric measurement of CAM lesion is feasible, fast and more reliable than alpha angle and the segmented volumes will exhibit significant anthropomorphic correlations.

METHODS

Study population

This retrospective study was approved by the Institutional Review Board and was conducted in compliance with the Health Insurance Portability and Accountability Act. Informed consent was waived. A consecutive series of adult FAI patients who underwent 3D pelvis CT between July 2013 and August 2016 were included in this study. Patients were referred as a convenience

sample from our institutional Sports Medicine clinic. Inclusion criteria were adult patients with final diagnosis of unilateral or bilateral clinically symptomatic CAM lesions who had undergone pre-operative 3DCT evaluation. The diagnosis was made by the sports hip surgeon using a combination of clinical findings, decreased range of motion and measurements on pelvis and hip radiographs in all patients. 33/43 (77%) also had surgery with femoral CAM plasty. Exclusion criteria were prior FAI surgery and a final diagnosis of isolated pincer deformity based on normal alpha angle and increased coronal or sagittal center edge angle. The pelvis and hip radiographs were routinely obtained prior to CT and used by surgeons and radiologists as part of the clinical care to arrive at the diagnosis of FAI. The CT measurements including alpha angle, coronal and sagittal center edge angle were also available from the formal reports generated as part of the clinical care.

CT examination

Image acquisition

Pelvis CT scans including both hips were obtained on multislice CT scanners (Optima 660–64 slice GE scanner and Aquilion TM-64 slice Toshiba scanner) using the following parameters: beam collimation (64 × 0.625 mm, tube voltage 120 kVp, and tube current 140–280 mAs). The images were acquired from L5 vertebra to the proximal femoral metadiaphysis. Automatic exposure control were used. The dose variability was related to BMIs of different patients scanned. The mean dose length product was 234 ± 149.63 milliGrey-centimeter and the mean CT dose index was 23.7 ± 6.04 milliGrey.

Image post processing and measurement

DICOM images were retrospectively imported into an independent image analysis software program (Tera Recon, Aquarius iNtuition, Foster City, CA). The software enabled creation of 3D volume rendered image of the pelvis with segmentation of the proximal femur. A region-grow color tool based on CT density was used to separately segment the femoral head and respective CAM lesion allowing automatic calculation of their volumes. Two readers, a radiology resident with 2 years (AG) and a radiologist with 8 years (LZ) of experience evaluated the images independently after a training set of 6 CT scans of FAI patients, blinded to the clinical reports or examination findings. The processing time required to obtain the segmentation and make the necessary measurements was recorded.

Table 1. Demographic and anthropometric features of study population

Variable	Mean ± SD
Age (years)	36.6 ± 11.47
Height (meters)	1.72 ± 0.10
BMI (kg m ⁻²)	26.25 ± 4.31
Male: female ratio	1:1.15
Flexion adduction and internal rotation (FADIR) positive	37/43
Flexion abduction and external rotation (FABER) positive	24/43

Table 2. Volumetric measurements for CAM and femoral head volumes among males and females

Volumetric measurement (cm ³)	Male mean (SD)	Female mean (SD)	Difference	P-value
CAM lesion (bump)	6.7 (2.5)	4.3 (3.4)	2.4	0.0009
Femoral head	62.9 (10.8)	41.8 (8.6)	21.1	<0.0001

Radial imaging was separately obtained by both readers with the same software using previously described methods¹⁹ (Supplementary figure 1). Alpha angles were then measured at 1 and 2 O'clock positions (Supplementary Figure 2). Patient demographics were recorded and all measurements of alpha angles, femoral head and CAM volumes were recorded on an excel

spread sheet (Microsoft excel 2010), and the femoral CAM bump/head volume ratio was calculated.

To ensure the measurement consistency, preoperative radiographs were evaluated for osteoarthritis grade as described by Tönnis and measured on AP pelvis radiographs.²⁰ The Tönnis

Figure 2. A 22-year-old male with height of 1.85 meters and BMI of 25.07 kg m⁻² shows (a) alpha angle = 67.3 degrees at 1 o'clock, (b) 60.9 degrees at 2 o'clock and, (c) volumes of CAM bump (4.26 cm³) and femoral head (66.5 cm³) on 3D segmented image.

Figure 3. Alpha angle measures at (a) 1 o'clock and (b) 2 o'clock positions in 39-year-old female with height of 1.70 meters and BMI of 21.4 kg m⁻².

Table 3. Alpha angles in males vs females

Alpha angle (degree)	Male mean (SD)	Female mean (SD)	Difference	p-value
1 O'clock	64.9 (7.4)	59.5 (9)	5.4	0.009
2 O'clock	65.1 (10.6)	59.4 (7.9)	5.7	0.046

classification of osteoarthritis was graded as 0 (no changes), 1 (widened sclerotic zone and 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).

Statistical analysis

Descriptive statistics were used to evaluate the patient demographics. Mean and SD were calculated for volumetric and alpha angles measurements. Pearson correlation coefficients were used to assess the associations between CAM volume, femoral head volume, CAM bump-head ratio, alpha angles, and age/height/BMI. Pearson partial correlations were also used to adjust the confounding factor of sex, when necessary. A 2-sample t-test was used to test the mean differences between females and males. p -value < 0.05 was considered statistically significant. Intraclass correlation coefficient (ICC) and Bland Altman plots were used to evaluate inter reader variability. ICC values were interpreted as follows: >0.75 was excellent, 0.40–0.75 was fair to good and <0.40 was poor.²¹ Bland Altman plots with limits of agreement (± 2 SD) were used to avoid variations in ICC due to variations in sample. SAS 9.4 (SAS Institute Inc., Cary, NC) was used for data analysis.

RESULTS

Study population

From July 2013 to August 2016, 58 patients with FAI were examined on CT. Nine patients with previous surgery for FAI and 6

patients with isolated pincer type FAI were excluded. 43 CAM type or mixed FAI patients were included in the final sample. Table 1 shows demographics, frequency of positive impingement tests and anthropomorphic features of the study population. 33/43 (77%) patients underwent femoroplasty.

CT imaging findings

CAM lesion and femoral head volumes

43 FAI patients had 56 CAM lesions (13 were bilateral with male: female ratio of 3.3:1). Successful segmentation could be performed in all cases and the average time needed to perform femoral head and CAM lesion segmentation and volumetric assessment was 4 min (range = 3 to 5 min per examination). The volume of CAM lesions ranged from 1.2 to 12.5 cm³ with mean $\pm$ SD of 5.57 ± 2.75 . The volume of femoral head ranged from 24.4 to 85.2 cm³ with mean $\pm$ SD of 52.75 ± 14.4 . Significantly higher mean CAM and femoral head volumes were observed in males as compared to females ($p = 0.0009$ and <0.0001, respectively) (Table 2, Figure 2).

Radial imaging and alpha angles

Radial imaging was obtained separately by both readers independently to generate femoral images at 1 and 2 O'clock positions. Mean and SD of alpha angles at 1 and 2 o'clock were 60.9 ± 9.2 and 61.9 ± 9.1 , respectively (Figure 3). Table 3 shows mean and SD of various alpha angles in males and females. Significantly higher mean alpha angle measurements were observed in males at both 1 and 2 o'clock positions when compared to females (p values of 0.009 and 0.046 at 1 and 2 O'clock, respectively). The

Figure 4. Correlations between femoral head and bump in males and females.

Figure 5. Bland-Altman plot showing limits of agreement (± 2 SD) between the readers with respect to the measurement of femoral head.

average time needed to perform angle measurements was 12 min (range = 10 to 14 min per examination).

Tönnis angles

Tönnis angles were measured for all hips on AP radiographs and graded for osteoarthritis. From the 56 hips examined on CT, 50 had an AP pelvis examination for measurement and grading. 18 hips had Tönnis grade 0 (36%), 23 hips had Tönnis Grade 1 (46%), 8 hips had Tönnis Grade 2 (16%) and 1 hip had Tönnis Grade 3 (2%).

Correlation between volumetric measures / alpha angles and anthropomorphic features

Significant correlations were observed between femoral head volume and height (Pearson correlation = 0.82, $p < 0.01$) and CAM volume and height (Pearson correlation = 0.45, $p < 0.06$) (Figures 4 and 5). The positive correlations between femoral head volume and height remained significant after adjusted for gender (Pearson partial correlation 0.59, $p < 0.01$), but not between CAM bump volumes and height (Pearson partial correlation 0.18, p value 0.18).

Significant correlations were also found between bump volume and femoral head volume (Pearson correlation coefficient 0.52 with males and females combined, p value < 0.01). Similar trends were observed in both male and female groups independently (after adjusting for gender, partial Pearson correlation = 0.33, $p = 0.01$) (Figure 4). No significant correlations were found between

alpha angles (at 1 and 2 o'clock) and volumetric measures, such as femoral head volume, bump volume and head-bump ratio (Pearson correlations of 0.14, 0.08 and 0.01 with p values of 0.36, 0.61 and 0.96 at 1 o'clock and Pearson correlations of 0.27, 0.23 and 0.11 with p values of 0.08, 0.14 and 0.48 at 2 o'clock positions, respectively). No significant correlations were found between alpha angles and various anthropometric features, such as patient age, height or BMI. Table 4 summarizes Pearson correlations and corresponding P -values for various volumetric, alpha angle, and anthropometric features.

Inter-reader agreement

For first and second readers, the mean head volume, bump volume, head/bump ratio and alpha angle measurements at 1 & 2 o'clock were 52.75 ± 14.4 , $5.57 \pm 2.75 \text{ cm}^3$, 0.11 ± 0.05 and 60.9 ± 9.2 , 61.9 ± 9.1 degrees and 54.48 ± 12.9 , 4.62 ± 1.89 , 0.08 ± 0.03 and 52.3 ± 8.8 , 55.3 ± 9.3 degrees respectively. Table 5 shows mean volumetric and alpha angle measurements and the absolute agreement among readers. Intraclass correlation coefficient was used to assess inter reader agreement. Volumetric measurements for femoral head, CAM lesion and CAM/head ratio showed excellent (ICC = 0.85, 95% CI 0.76 to 0.91), fair to good (ICC = 0.48, 95% CI 0.25 to 0.66) and poor (ICC = 0.34, 95% CI 0.09 to 0.56) inter reader agreements, respectively (Figures 5–7). All alpha angles showed poor interobserver agreements (ICC of 0.12, 95% CI –0.15 to 0.39 and 0.19, 95% CI –0.09 to 0.45 for 1 and 2 O'clock, respectively) (Figures 8 and 9).

Table 4. Correlations for various volumetric, alpha angle, and anthropometric features (significant correlations are bold)

Measurement	Parameter	Pearson correlation coefficient	p -value
Femoral head volume (cm^3)	Height	0.82	<0.01
	Height (adjusted for gender)	0.59	<0.01
Bump volume (cm^3)	Height	0.45	<0.06
	Height (adjusted for gender)	0.18	0.18
	Femoral head volume	0.52	<0.01
	Femoral head volume (adjusted for gender)	0.33	0.01
Alpha angle at 1 o'clock (degrees)	Head volume	0.14	0.36
	Bump volume	0.08	0.62
	Head/bump ratio	0.01	0.96
Alpha angle at 2 o'clock (degrees)	Head volume	0.27	0.08
	Bump volume	0.23	0.14
	Head/bump ratio	0.11	0.48

Table 5. Mean individual reader measurements with absolute agreement

Parameter	Reader 1 mean (SD)	Reader 2 mean (SD)	Mean (SD) difference
Head volume	52.75 (14.4)	54.48 (12.9)	–1.71 (21.2)
Bump volume	5.57 (2.75)	4.62 (1.89)	0.94 (3.4)
Head/bump ratio	0.11 (0.05)	0.08 (0.03)	0.02 (0.05)
Alpha angle at 1 o'clock	60.9 (9.2)	52.3 (8.8)	9.6 (13.6)
Alpha angle at 2 o'clock	61.9 (9.1)	55.3 (9.3)	7.7 (13.7)

Figure 6. Bland-Altman plot showing limits of agreement (± 2 SD) between the readers with respect to the measurement of CAM volume.

DISCUSSION

CAM femoroacetabular impingement is a clinical condition believed to be linked to professional athletes in the adolescent period.²² It has recently gained scientific and surgical importance due to its association with premature osteoarthritis, however, no consensus on optimum diagnostic and treatment strategy has been established.²³ Over the past decade, literature has recognized the three dimensional and dynamic nature of the disease, questioning and accuracy of two dimensional (alpha angle) measurements,^{17,24–27} even when performed on radial imaging planes.^{25,28,29} While attempts have been made for preoperative characterization of CAM morphology using surface area and volumetrics on 3DCT,^{18,30,31} the studies were limited by complex reconstruction methods and limited generalizability in clinical practice. In this study, we aimed to evaluate the feasibility and

Figure 7. Bland-Altman plot showing limits of agreement (± 2 SD) between the readers with respect to the measurement of CAM/femoral head ratio.

Figure 8. Bland-Altman plot showing limits of agreement (± 2 SD) between the readers with respect to the measurement of alpha angle at 1 O'clock position.

reliability of a simplified volumetric CAM measurement method as a possible alternative to the traditionally advocated radial imaging with alpha angle measurements on 3DCT

Our findings showed that software segmentation and volumetric measurements are feasible, fast and more reliable than alpha angle measurements. Both readers performed segmentation with volumetric measurements three times faster than radial imaging with alpha angle measurements on average (4 vs 12 min respectively) and volumetric measurements showed superior (good to excellent) inter reader reliability to alpha angle (poor) measures. In addition, statistically significant correlations between anthropomorphic features and volumetric measurements were found. Significant positive correlations were found between femoral head and bump volume in males. This finding agreed with a previous study by Yanke *et al.*³² Significant correlations were

Figure 9. Bland-Altman plot showing limits of agreement (± 2 SD) between the readers with respect to the measurement of alpha angle at 2 O'clock position.

also found between patient height and both femoral head and CAM volumes. To our knowledge, this finding has not been previously reported and might be an important, but currently unknown factor to be considered in pre-surgical planning. Ross et al reported that residual deformity is observed in up to 90% of patients undergoing revision surgery for symptomatic FAI patients and the true extent of CAM deformity can be measured by volumetric analysis or omega angle.³³

Other findings were higher alpha angles in males at both 1 and 2 o'clock positions. This agreed with recent studies showing male predilection for higher alpha angles^{15,16,34} and raises the question of redefining higher cutoff values for diagnosis of CAM femoroacetabular impingement. Higher alpha angles were found at 1 and 2 o'clock positions. This was expected as also reported previously studies with anterosuperior location being the most common location of the CAM bump.^{16,29,35,36} Finally, bilateral CAM lesions were more common in males, with a male to female ratio of 3.33:1. This was similar to a previous study reporting a 3:1 ratio for bilateral hip involvement.³⁷ Despite gender correlations, no significant correlations were found between the alpha angles and other anthropomorphic features or volumetric measurements.

These findings of variability with patient height and sex may have important implications in terms of amount of CAM resection surgeon will have to perform, with males and taller patients needing more CAM resection. In addition, these bump variations may have implications in terms of the amount of articular cartilage loss and extent of labral tears, which remains to be studied. The 3D-region grow tool for segmentation is fast and can be used to outline the whole CAM lesion for pre-surgical mapping. It remains to be seen whether calculated volumes

may serve as surrogate imaging markers for outlining treatment strategies or patient outcomes. In future, automated algorithms may become commercial and compute these volume measurements and produce 3D prints, thereby further enhancing the reliability.^{30,38,39}

Our study has several limitations including the retrospective nature. 77% patients from our study underwent femoroplasty but the CAM lesion measurements were not prospectively recorded. Another drawback is the absence of a control group for comparison and a sampling bias, including only pre-operative patients who had 3DCT. This was not feasible, since volumetric measurements relied on the presence of anatomic deformity (CAM lesion) at the femoral head neck junction. In future, the segmentation method could be used for pre-operative planning and intra operative correlations can be obtained with caliper measurements of the CAM lesion. Furthermore, these measurements can be automated and correlated with clinical findings, as well as with the extent of labral tears and cartilage injury observed during surgery or concurrent MR imaging. Finally, about 18% of study patients had Tönnis Grades 2 and 3, but it represented the consecutive series of pelvis CTs with FAI protocol and those who got operated. It represented our University setting practice and hip surgeon's practice pattern.

To summarize, volumetric segmentation of femoral head and CAM lesions is an easily applicable, fast and reliable method on 3DCT to quantify the CAM lesions with good interreader reliability. Significant correlations exist between the CAM lesion volume, patient height and male gender. Future prospective studies with surgical correlations can further validate our findings.

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