CT-based 3D analyses show similarities in anterior-superior acetabular coverage between acetabular dysplasia and borderline dysplasia.

Running title: 3D Coverage of Borderline Hip Dysplasia

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Abstract

Purpose: (1) To compare the acetabular coverage between dysplasia, borderline dysplasia, and control acetabulum in a quantitative three-dimensional manner, and (2) to evaluate correlations between the radiologic parameters and the three-dimensional zonal-acetabular coverage. **Methods:** We reviewed contralateral hips CT images of sixteen to sixty years old patients who underwent one of three types of surgeries: eccentric rotational acetabular osteotomy, curved intertrochanteric varus osteotomy, and total hip replacement with minimum 1-year follow-up from January 2013 to April 2018. A point-cloud model of the acetabulum created from CT was divided into 6 zones. Three-dimensional acetabular coverage was measured radially at intervals of 1 degree. Mean radial acetabular coverage for each zone was named ZAC (*Zonal Acetabular Coverage*) and was compared among the three sub-groups (control: 25°≤lateral center-edge angle [LCEA]<40°; borderline: 20°≤LCEA<25°; and dysplasia: LCEA≤20°) statistically. Further, the correlations between the ZAC in each zone and the LCEA were analyzed using Pearson's correlation coefficient. **Results:** One-hundred and fifteen hips were categorized as: control (36 hips); borderline (32 hips); and dysplasia (47 hips). The mean antero-cranial ZAC in the borderline (87.5±5.7°) was smaller than that in the control (92.6±5.9°, p=0.005), but did not differ compared with the dysplasia (84.5±7.6°, p=0.131). In contrast, the antero-caudal (71.2±5.0°), postero-cranial (85.0±6.4°), and postero-caudal (82.4±4.5°) mean ZACs in the borderline were not different from those in the control (antero-caudal, 74.3±4.6°, p=0.090; postero-cranial, 87.9±4.3°, p=0.082; postero-caudal, 85.1±5.0°, p=0.069) respectively. Although there was a very strong positive correlation with supra-anterior ZAC and LCEA (r=0.750, p<0.001), the correlation between the antero-cranial ZAC and LCEA was relatively weak (r=0.574, p<0.001). **Conclusions:** The anterior-superior acetabular coverage in the borderline dysplastic acetabulum is more similar to the dysplastic acetabulum than to the normal acetabulum. **Clinical Relevance:** This study

emphasizes the importance of evaluating not only the lateral but also the anterior coverage in borderline dysplasia.

Introduction

Borderline hip dysplasia is defined radiologically using anteroposterior (AP) pelvic radiographs and the most commonly used definition is hips with lateral center-edge angle (LCEA) 20° to 25°.[1–3] Labrum tears and cartilage damages are often observed in both dysplastic and borderline dysplastic hips.[3–6] Isolated arthroscopic treatment is not recommended in the setting of dysplasia owing to reports of the inferior clinical outcomes and iatrogenic instability.[7,8] However, there is limited evidence to suggest that the isolated arthroscopic treatment may be considered in cases of borderline dysplasia when careful attention is paid to labral and capsular preservation.[9–13]

The hip joint is usually modeled as a ball-and-socket joint and the acetabular bony morphology is recognized as the first stabilizer.[141516] Borderline dysplasia represents a "transitional acetabular coverage" between acetabular dysplasia and normal coverage. Therefore, it is essential to clarify how the three-dimensional acetabular coverage in borderline dysplasia differs from dysplasia or normal acetabulum in order to determine the treatment strategy.

Whether the isolated arthroscopic treatment improves the long-term outcomes of borderline dysplastic hips remains controversial.[31014] Moreover, patient selection criteria remains unclear although careful patient selection is necessary to determine successful treatment.[17] A smaller vertical center anterior (VCA) angle has been reported as a predictor of poor clinical outcome after isolated hip arthroscopy for borderline dysplasia.[3] This report suggests that zonal-acetabular coverage such as anterior coverage can affect the outcomes. Therefore, it is important to evaluate the three-dimensional acetabular coverage for good clinical outcome.[3] However, there is scarce information on methods and clinical data on three-dimensional acetabular coverage in borderline dysplasia. It would be critical data when considering management for patients with borderline dysplasia in an effort to optimize surgical results and minimize the potential for complications.

AP pelvic radiograph is the golden standard radiographic examination for patient with symptomatic hip, and both LCEA and Tönnis angle[18] are measured on the AP pelvic radiograph. Borderline dysplasia is classified based on the LCEA. Meanwhile, many surgeons are skeptical that the LCEA is a sufficient surrogate marker for entire acetabular coverage including anterior and posterior coverage.[19] Besides, a larger Tönnis angle has also been reported as a predictor of poor clinical outcome after arthroscopy for borderline dysplasia.[3] Therefore, it can be meaningful to clarify the relationship between three-dimensional zonal-acetabular coverage and radiologic parameters such as LCEA or Tönnis angle.

The two objectives of this study were: (1) to compare the acetabular coverage between dysplasia, borderline dysplasia, and control acetabulum in a quantitative three-dimensional manner, and (2) to evaluate correlations between the radiologic parameters and the three-dimensional zonal-acetabular coverage. We hypothesized that LCEA would be an insufficient surrogate marker for the entire acetabular coverage, especially anterior or posterior coverages.

Methods

Patients and Study Design

This study was approved by the institutional review board. Sixteen to sixty years old patients who underwent one of three types of surgeries: a) eccentric rotational acetabular osteotomy (ERAO)[20] for acetabular dysplasia, b) curved intertrochanteric varus osteotomy (CVO)[21] for idiopathic osteonecrosis of the femoral head (ONFH), and c) total hip replacement (THR) for ONFH or osteoarthritis (OA) from January 2013 to April 2018 at our institution were included and contralateral hips of those patients were evaluated in this study. Exclusion criteria were: (1) prior hip surgery or trauma; (2) LCEA ≥ 40°; (3) ONFH; (4) radiographic OA (Kellgren-Lawrence Grade 1, 2, 3 or 4); (5) subluxation; (6) aspherical femoral head; or (7) follow-up period less than 1 year. The hips were categorized based on LCEA as: control group (25° ≤ LCEA < 40°), borderline group (20° ≤ LCEA < 25°) and dysplasia group (LCEA < 20°).

Indication for ERAO were: (1) pain lasting more than 6 months with conservative treatment; (2) patients between the ages of 15 and 55 years who want to preserve joints; (3) prearthritis, early-stage and advanced-stage arthritis with minimum joint space width of > 2 mm.[22] Indication for CVO were: (1) patients under 55 years old who want to preserve joints; (2) the Japanese Investigation Committee (JIC) classification type B, type C1 or C2;[23] and (3) lateral head index, which is a radiographic parameter for assessing the area of the intact portion, > 25% at maximum hip abduction position.[24] Indication for THR were: (1) pain lasting more than 6 months with conservative treatment and (2) patients who do not fit ERAO or CVO indication.

All patients underwent bilateral hip CT scans, MRIs, and supine AP pelvic radiographs taken by Siebenrock's standardized technique for preoperative examinations.[25] CT images, MRIs, and AP pelvic radiographs were obtained within 7 days for each patient. LCEA of Wiberg[1] (Fig. 1A), Tönnis angle[18] (Fig. 1B), radiographic OA were evaluated by AP radiographs. Acetabular anteversion angle (AcAV) was determined in the axial plane passing through the femoral head center as the angle formed by the intersection of a line connecting the anterior and posterior edges of the acetabulum and a sagittal line (Fig. 1C).[26] ONFH was confirmed by both AP radiographs and MRIs. A break in the Shenton line on AP radiographs of > 5 mm was defined as joint subluxation.[27]

Three-dimensional Model Creation and Definition of an Acetabular Spherical Coordinate System

All patients underwent a helical CT scan (CT High Speed Advantage; GE Medical Systems, Milwaukee, WI, USA) in the supine position covering both hips at 0° of flexion, neutral abduction/adduction and neutral internal/external rotation. Slice thickness and interval were set at 1 mm each, and table speed was set at 1 mm/s. CT images of each hip joint were imported in DICOM format and segmented using a segmentation software (Mimics 21R, Materialise, Leuven, Belgium). Images were reconstructed to three-dimensional (3D) femoral and coxal bone models, and then the resulting 3D models were exported as point-cloud, mesh and standard tessellation language models using the same software package. The 3D femoral and coxal bone models were then analyzed with a custom-written program created in Microsoft Visual C++ with Microsoft Foundation Class programming environment (Microsoft, Redmond, WA).[28,29]

The femoral head center was calculated using a custom-written program according to the technique described by Yanke *et al*.[28–30] The center of the *fossa acetabuli* was identified using the same software and the line connecting this center and the femoral head center was set as a reference axis in order to avoid confounding from variable patient positioning in the CT gantry[31] (Fig. 2A). The most anterior-inferior corner point and posterior-inferior corner point of the lunate surface were manually identified on the 3D coxal bone models. Based on the identified anterior-inferior corner point and posterior-inferior corner point, the midpoint between these two corner points was calculated as an acetabular notch midpoint. Positions within the lunate surface were described by a spherical coordinate system with an acetabular notch midpoint being 0° position (Fig. 2A).

Three-dimensional Acetabular Coverage Evaluation

Radial Acetabular Coverage: The acetabular rim border points were automatically detected from each coxal bone model using a custom-written program (Fig. 2B). The rim border points and the femoral head center were connected radially at intervals of 1 degree. These angular positions spanned from 45 to 315 degrees on the acetabular clock face (with 180 degrees oriented in the cranial direction). At each discrete angular position, the acetabular coverage was measured and recorded as the radial acetabular coverage (Fig. 2C).

Zonal-acetabular Coverage: The left lunate surface model was divided into six zones as follows: antero-caudal zone, from 45° to 90°; antero-cranial zone, from 90° to 135°; supra-anterior zone, from 135° to 180°; supra-posterior zone, from 180° to 225°; postero-cranial zone, from 225° to 270°; and postero-caudal zone, from 270° to 315° (Fig. 2D). The right side of the hip was zoned in the same way. The mean of 45 radial acetabular coverage measurements in each zone was calculated as zonal-acetabular coverage.

Statistical Analysis

The *chi*-square test was used to compare categorical parameters among the three groups. The radial acetabular coverage measurements from 45 degrees to 315 degrees were compared statistically at 15 degree intervals among the three groups using ANOVA with Tukey's *post hoc* test. The zonal-acetabular coverage measurement in each zone was also compared statistically in a same manner. Further, the correlations between the zonal-acetabular coverage measurement in each zone and the radiologic parameters (LCEA, Tönnis angle, and AcAV) were analyzed using Pearson's correlation coefficient. Pearson's correlation (r) was graded as follows: $\geq +0.7$ or ≤ -0.7 (very strong positive or very strong negative, respectively), +0.40 to +0.69 or −0.69 to −0.40 (strong positive or strong negative, respectively), +0.30 to +0.39 or −0.39 to −0.30 (moderate positive or moderate negative), +0.20 to +0.29 or −0.29 to −0.20 (weak positive or weak negative), +0.19 to −0.19 (no or negligible relationship).[32] Statistical analyses were performed using JMP Pro 14 software (SAS Institute Japan, Tokyo, Japan). Data is presented as mean ± SD and the corresponding 95% confidence intervals. Significance was set at $p < 0.05$.

Results

Patient Demographics

Between January 2013 and April 2018, ERAO, CVO, and THR were performed in 71 patients, 44 patients, and 50 patients respectively and 165 contralateral hips were evaluated. Six hips had undergone prior hip surgery, three hips had LCEA ≥ 40°, 17 hips had ONFH, eighteen hips had radiographic OA, four hips had subluxation, and two hips had aspherical femoral heads. Those fifty hips were excluded (Fig. 3). The remaining one-hundred and fifteen hips were categorized as: control group, thirty-six hips; borderline group, thirty-two hips; and dysplasia group, forty-seven hips. In the control group, twenty-one hips were from male patients, and fifteen hips were from female patients. In the borderline group, eleven hips were from male patients, and twenty-one hips were from female patients. In the dysplasia group, seven hips were from male patients, and forty hips were from female patients (Fig. 3). No differences were noted among the three groups in weight or body mass index (BMI). However, there were differences in the age, sex, or height (Table 1).

Radiologic Parameters

The mean LCEA of the borderline group (23.3 ± 1.4°) was significantly smaller than the control group (30.0 ± 5.5° , $p < 0.001$) and significantly larger than the dysplasia group (10.7 ± 5.1° , p <

0.001). The mean Tönnis angle of the borderline group (10.6 ± 4.3°) was significantly larger than the control group (3.0 ± 5.4° , $p < 0.001$) and significantly smaller than the dysplasia group (19.3 ± 5.7° , $p < 0.001$). Although the mean acetabular anteversion angle of the borderline group (21.3 ± 3.7°) was significantly larger than control group (17.9 ± 3.5° , $p = 0.001$), that of the borderline group was not significantly different from the dysplasia group (23.3 ± 4.0° , $p = 0.053$) (Table 2).

Radial Acetabular Coverage

The mean radial acetabular coverage values at 150°, 165°, 180°, 195°, and 210° angular positions in the borderline group were significantly smaller than in the control group and larger than in the dysplasia group respectively. Although the coverage values at 45°, 60°, 75°, 90°, 225°, 240°, 255°, 270°, 285°, 300°, and 315° in the borderline group were not significantly different from those in the control group, they were significantly larger than in the dysplasia group respectively. The coverage at 105°, 120°, and 135° angular positions in the borderline group was significantly smaller than those in the control group although they were not significantly different from those in the dysplasia group respectively (Fig. 4).

Zonal-acetabular Coverage

The mean antero-cranial zonal-acetabular coverage in the borderline group (87.5 ± 5.7°) was significantly smaller than that in the control group (92.6 ± 5.9°, $p = 0.005$), but did not significantly differ compared with the dysplasia group (84.5 ± 7.6°, $p = 0.131$). In contrast, the antero-caudal (71.2 ± 5.0°), postero-cranial (85.0 ± 6.4°), and postero-caudal (82.4 ± 4.5°) mean zonal-acetabular coverage values in the borderline group were not significantly different from those in the control group (antero-caudal, 74.3 ± 4.6°, $p = 0.090$; postero-cranial, 87.9 ± 4.3°, $p = 0.082$; and postero-caudal, 85.1 ± 5.0°, $p = 0.069$) , and significantly larger than those in the dysplasia group (antero-caudal, 63.8 ± 7.2°, $p < 0.001$; postero-cranial, 79.9 ± 5.8°, $p < 0.001$; and postero-caudal, 76.0 ± 5.1°, $p < 0.001$) respectively (Fig. 5).

Correlations between Zonal-acetabular Coverages and Radiologic Parameters.

In the supra-anterior zone, there was a very strong positive correlation with zonal-acetabular coverage value and LCEA ($r = 0.750$, $p < 0.001$). For the other five zones, there were strong positive correlations with zonal-acetabular coverage values and LCEA (antero-caudal; $r = 0.596$, $p < 0.001$, antero-cranial; $r = 0.574$, $p < 0.001$, supra-posterior; $r = 0.608$, $p < 0.001$, postero-cranial; $r = 0.611$, $p < 0.001$, and postero-caudal; $r = 0.613$, $p < 0.001$). Regarding the correlation between zonal-acetabular coverage values and Tönnis angle, there were strong negative correlations in all zones (antero-caudal; $r = -0.548$, $p < 0.001$, antero-cranial; $r = -0.514$, $p < 0.001$, supra-anterior; $r = -0.661$, $p < 0.001$, supra-posterior; $r = -0.494$, $p < 0.001$, postero-cranial; $r = -0.505$, $p < 0.001$, and postero-caudal; $r = -0.554$, $p < 0.001$). With respect to the correlation between zonal-acetabular coverage values and AcAV, there were moderate negative correlations in the antero-caudal zone ($r = -0.322$, $p < 0.001$) and the supra-anterior zone ($r = -0.312$, $p < 0.001$). Although there were weak negative correlations in the antero-cranial zone ($r = -0.243$, $p = 0.009$) and the supra- posterior zone ($r = -0.206$, $p = 0.027$), neither the postero-cranial zone ($r = -0.159$, $p = 0.091$) nor the postero-caudal zone ($r = -0.195$, $p = 0.036$) (Table 3) showed correlation.

Discussion

The principal finding in this study is that the anterior-superior acetabular coverage in the borderline dysplastic acetabulum was more similar to the dysplastic acetabulum than to the normal acetabulum (Fig. 4 and 5).

Since acetabular dysplasia is a three-dimensional deformity, three-dimensional evaluation of entire acetabular coverage is critical in an effort to optimize surgical results. The present results show that the radial acetabular coverage in the borderline group was the smallest at 45°, peaked towards the range from 135° to 180°, and then decreased again toward 315° (Fig. 4). This trend was similar to the reported dysplastic coverage or normal one.[33–35]

Acetabular dysplasia is primarily assessed on the lateral coverage by LCEA. However, early osteoarthritis is more highly associated with anterior acetabular deficiency than with lateral deficiency.[27] Surprisingly, a multicenter study, grouped based on LCEA, did not show significant differences in outcomes after hip arthroscopy in patients with either borderline undercoverage, normal coverage, and overcoverage.[13] In contrast, a smaller VCA angle has been reported as a predictor of poor clinical outcome after hip arthroscopy for borderline dysplasia.[3] The VCA angle is recognized as an indicator of anterior coverage. Therefore, these reports and our results demonstrate the importance of evaluating not only the lateral coverage but also the anterior coverage in borderline dysplasia.

The supra-anterior and supra-posterior zonal-acetabular coverages in the borderline group were significantly smaller than in the control group and significantly larger than in the dysplasia group (Fig. 5). LCEA represents the superior (in other words the “lateral”) acetabular coverage.[36] Hence, it was reasonable that the supra-anterior and supra-posterior zonal-acetabular coverages in the borderline group indicated intermediate values between the control group and the dysplasia group.

The antero-caudal, postero-cranial, and postero-caudal zonal-acetabular coverages in the borderline group were not significantly different from those in the control group, and were significantly larger than those in the dysplasia group respectively. We can interpret the present results as showing that the acetabular coverage of borderline dysplasia is focally reduced in the antero-cranial zone (Fig. 4 and 5). Jacobsen *et al.* reported that anterior acetabular sector angle of the borderline dysplasia was smaller than that of normal acetabulum.[37] Our results support this report. Dysplasia has several deficiency patterns. Nepple *et al*. reported that three patterns of acetabular deficiency were common with the following proportions: a) anterosuperior deficiency: 30%, b) global deficiency: 36%, and c) posterosuperior deficiency: 34%.[38] Ito *et al*. also reported that three patterns were common: anterior deficiency: 26%, lateral deficiency: 54%, and posterior deficiency: 20%.[39] The results presented herein suggest that borderline dysplastic hips are very likely to display an anterosuperior deficiency pattern. Further studies on borderline dysplasia deficiency patterns would clarify the association between them and dysplasia severity.

Only in the supra-anterior zone, there was a very strong positive correlation between the zonal-acetabular coverage and LCEA (Table 3). There are several reports evaluating the relationship between LCEA and lateral coverage measurements based on CT or MRI. Wylie *et al*. reported that sagittal location of the sourcil-edge LCEA is more anterior compared with the maximum bone LCEA.[36] Stelzeneder *et al*. also reported that a coronal MRI slice 10 mm anterior of the femoral head center is the best estimator of LCEA.[40] Although these reports were based on cross-sectional imaging data, the most lateral point of the sclerotic weight-bearing portion on AP radiograph, which is used for LCEA measurements, is assumed to be included in the supra-anterior zone in this study. Hence, it is reasonable that there was a very strong correlation between the supra-anterior zonal-acetabular coverage and LCEA. On the other hand, it is clinically important to examine where LCEA measured point by AP radiograph matches in the actual acetabular rim three-dimensionally. However, we have not evaluated it in this study. Positional relationship between the point measured by LCEA and the actual acetabular rim portion on the spherical coordinate system can differ depending on the individual acetabular morphology and pelvic orientation, which is affected by hip flexion contracture, lumbar lordosis, or kyphosis etc.[41–43] Therefore, we need to evaluate these positional relationships in the future study.

The antero-cranial zone is adjacent to the supra-anterior zone (Fig. 2D). Nevertheless, the correlation between the antero-cranial zonal-acetabular coverages and LCEA was relatively weak ($r = 0.574$) (Table 3) among the six zones although it was a strong correlation. LCEA may be an insufficient surrogate marker for entire acetabular coverage, especially anterior coverage. We believe that the three-dimensional acetabular coverage evaluation is exceedingly meaningful to the diagnosis of dysplasia and borderline dysplasia. Meanwhile, three-dimensional evaluation using CT data is not yet common in the clinic, and is discouraged from the radiation dose point of view. From this perspective, there is an advantage in assessment based on a plain radiograph. Although the VCA angle, measured on the false profile view, could vary according to the degree of pelvic inclination or rotation, it is a candidate for anterior coverage surrogate marker.[43–46] The VCA angle may show a stronger correlation with the antero-cranial zonal-acetabular coverage than the LCEA. If the cutoff value can be set based on the correlation between VCA angle and the antero-cranial zonal-acetabular coverage, it can be very useful in clinical practice. We believe that our results contribute meaningful basic datasets to set the cutoff value. Further studies are needed to probe associations between the present results and anterior coverage parameters like VCA.

Acetabular retroversion in dysplastic hips is also associated with decreased femoral head coverage independently from LCEA.[47] However, our results did not show very strong or strong correlation between AcAV and the zonal-acetabular coverage (Table 3). There was a moderate negative correlation in antero-caudal zone, and there was a weak negative correlation in antero-cranial zone. It has been reported that AcAV in the anterior deficiency pattern was larger than those in the normal and global deficiency pattern.[48] Negative correlations between AcAV and zonal-acetabular coverages in antero-caudal and antero-cranial zones may reflect the anterior deficiency pattern. In contrast, there was no correlation in postero-cranial or postero-caudal zone. Both anterior coverage and posterior coverage affect AcAV.[48] Since anterior coverage can negate the effects of posterior coverage, AcAV and zonal-acetabular coverages in postero-cranial and postero-caudal zones may not show a correlation.

Identification of the femoral head center is the key to quantitative evaluation of acetabular coverage in both two and three-dimensional manner. It is recognized that since we should determine the center of the femoral head to measure LCEA, the reliability of LCEA is slightly worse than that of Tönnis angle.[49–51] The method of Anderson *et al.* was reported to have higher reliability than the conventional method.[52] Therefore, we performed measurements using this method in identifying the center of the femoral head on the AP pelvic radiograph. Besides, multiple studies have used the centroid of the femoral head as the three-dimensional femoral head center.[34,53,54] However, the fovea capitis and the head-neck junction morphology can influence the calculation of the centroid of the femoral head. Therefore, in identifying the femoral head center on three-dimensional manner, we excluded the fovea capitis and the head-neck junction from the region of interest.[30]

Limitations

We note several limitations in this study. First, no association between the acetabular morphology and symptoms was evaluated. We only focused on comparing the acetabular morphology of borderline dysplasia with that of dysplasia and controls as that was the primary outcome. Additionally, the correlations between the zonal-acetabular coverage measurement and the anterior coverage radiologic parameter were not analyzed although these are important clinical issues contributing to the patient selection for the arthroscopic treatment. Second, the cohort we studied was a very specific patient group. For obvious reasons, CTs cannot be performed on healthy subjects with the intent of just conducting research. Therefore, the contralateral hip CT data from preoperative examinations was used instead. Consequently, there was a difference in the intragroup ratio of male versus female and some patient demographics differed between dysplasia group and control group. Hence, our results are difficult to generalize. Third, the radiologic parameters were measured by a single reader and the anterior-inferior corner point and posterior-inferior corner point of the lunate surface were manually identified to set a spherical coordinate system. Furthermore, the reliability of these parameters has not been evaluated in this study.

Conclusions

Our data shows that the anterior-superior acetabular coverage in the borderline dysplastic acetabulum is more similar to the dysplastic acetabulum than to the normal acetabulum.

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Legends

Fig. 1 A - C Measurements of the radiologic parameters. (A) Lateral center-edge angle (LCEA) on AP pelvic radiograph. (B) Tönnis angle on AP pelvic radiograph. (C) Acetabular anteversion angle (AcAV) on axial CT image.

Fig. 2 A - D Workflow to evaluate the three-dimensional acetabular coverage. (A) Setting of the acetabular reference axis. (B) Evaluation of the three-dimensional acetabular rim morphology. (C) Measurement of the radial acetabular coverage at different angular positions. The anterior wall is partially resected in order to visualize the center of fossa acetabuli and the reference axis. (D) Established the six zones of the lunate surface. AIC: anterior-inferior corner of the acetabular notch, PIC: posterior-inferior corner of the acetabular notch, CFA: center of fossa acetabuli, FHC: femoral head center.

Fig. 3 Flowchart showing the selection of hips to be evaluated and the actual number of hips in each group.

Fig. 4 Mean radial acetabular coverage in the borderline group relative to those in the dysplasia or control group shown in 15-degree intervals from 45° to 315°. The red outlined arcs denote that the coverages of the borderline are larger than those of the dysplasia. The green outlined arc denotes that the coverages of the borderline are smaller than those of the control. The yellow outlined arc denotes that the coverages of the borderline are larger than those of the dysplasia and smaller than those of the control. Significance was set at $p < 0.05$.

Fig. 5 Bar graphs showing the zonal-acetabular coverage of each zone in each group. Error bars span one SD.

Table 1. Patient demographics in each group

	Control	Borderline	Dysplasia	p value, overall
Age (years)	44 ± 14 (39-48)	42 ± 14 (37-47)	36 ± 13 (32-39)	0.019
Sex (male /female)	21/15	11/21	7/40	0.001
Weight (kg)	62 ± 11 (58-66)	60 ± 14 (55-66)	57 ± 13 (53-61)	0.232
Height (cm)	164 ± 7 (161-166)	162 ± 10 (158-165)	159 ± 7 (157-161)	0.013
BMI (kg/m^2)	23 ± 3 (22-24)	23 ± 4 (22-24)	23 ± 5 (21-24)	0.919

Values of continuous parameters are expressed as mean ± SD with 95% confidence interval in parentheses; BMI = body mass index.

Table 2. Radiologic parameters in each group

	Control	Borderline	Dysplasia	p value		
				Borderline vs. Control	Borderline vs. Dysplasia	Dysplasia vs. Control
Lateral center-edge angle (°)	30.0 ± 5.5 (28.2-31.9)	23.3 ± 1.4 (22.8-23.9)	10.7 ± 5.1 (9.2-12.2)	< 0.001	< 0.001	< 0.001
Tönnis angle (°)	3.0 ± 5.4 (1.1-4.8)	10.6 ± 4.3 (9.0-12.2)	19.3 ± 5.7 (17.6-21.0)	< 0.001	< 0.001	< 0.001
Acetabular anteversion angle (°)	17.9 ± 3.5 (16.7-19.1)	21.3 ± 3.7 (19.9-22.6)	23.3 ± 4.0 (22.1-24.5)	0.001	0.053	< 0.001

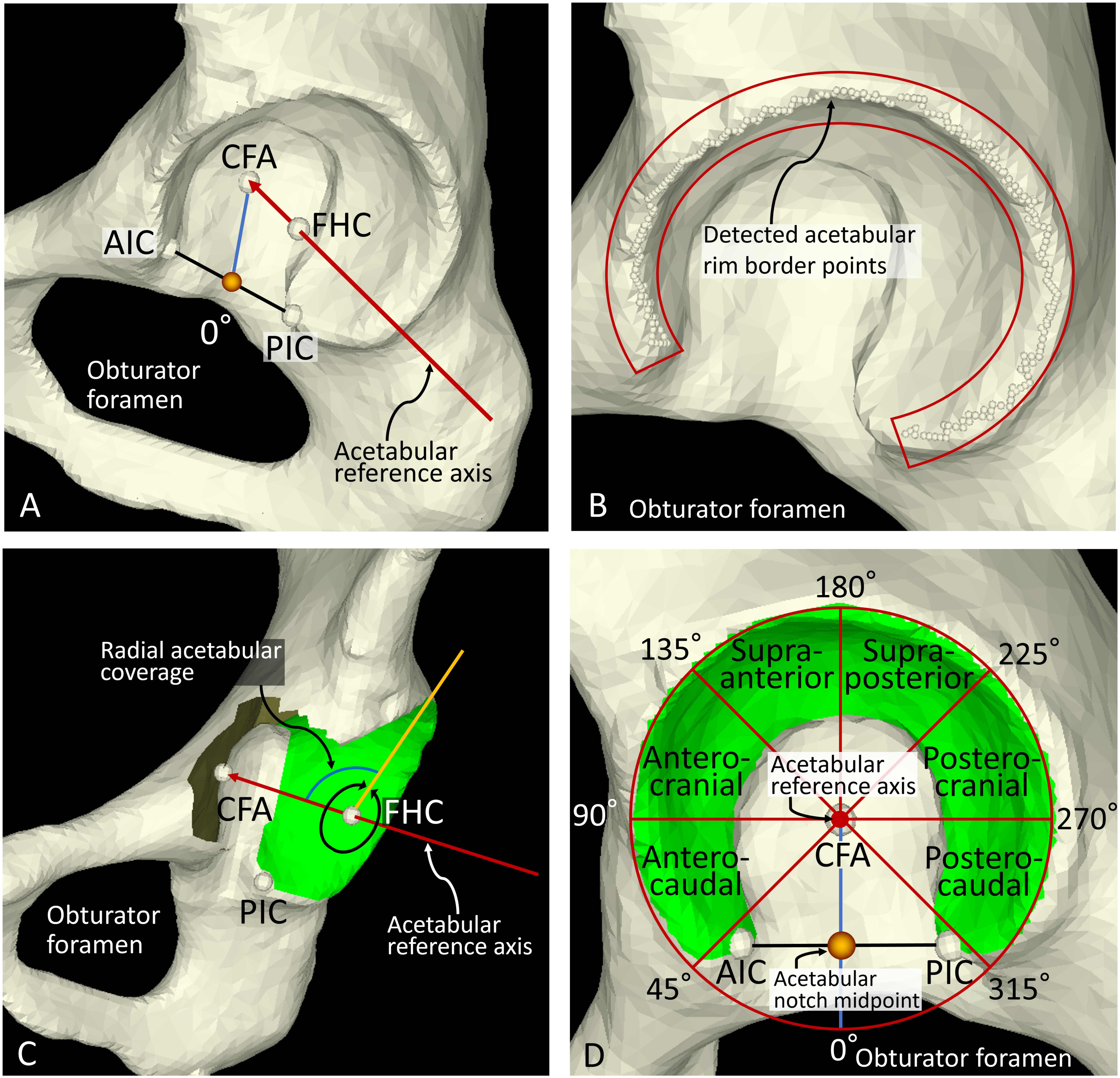
Values are expressed as mean ± SD with 95% confidence interval in parentheses.

Table 3. Correlations between zonal-acetabular coverages and radiologic parameters.

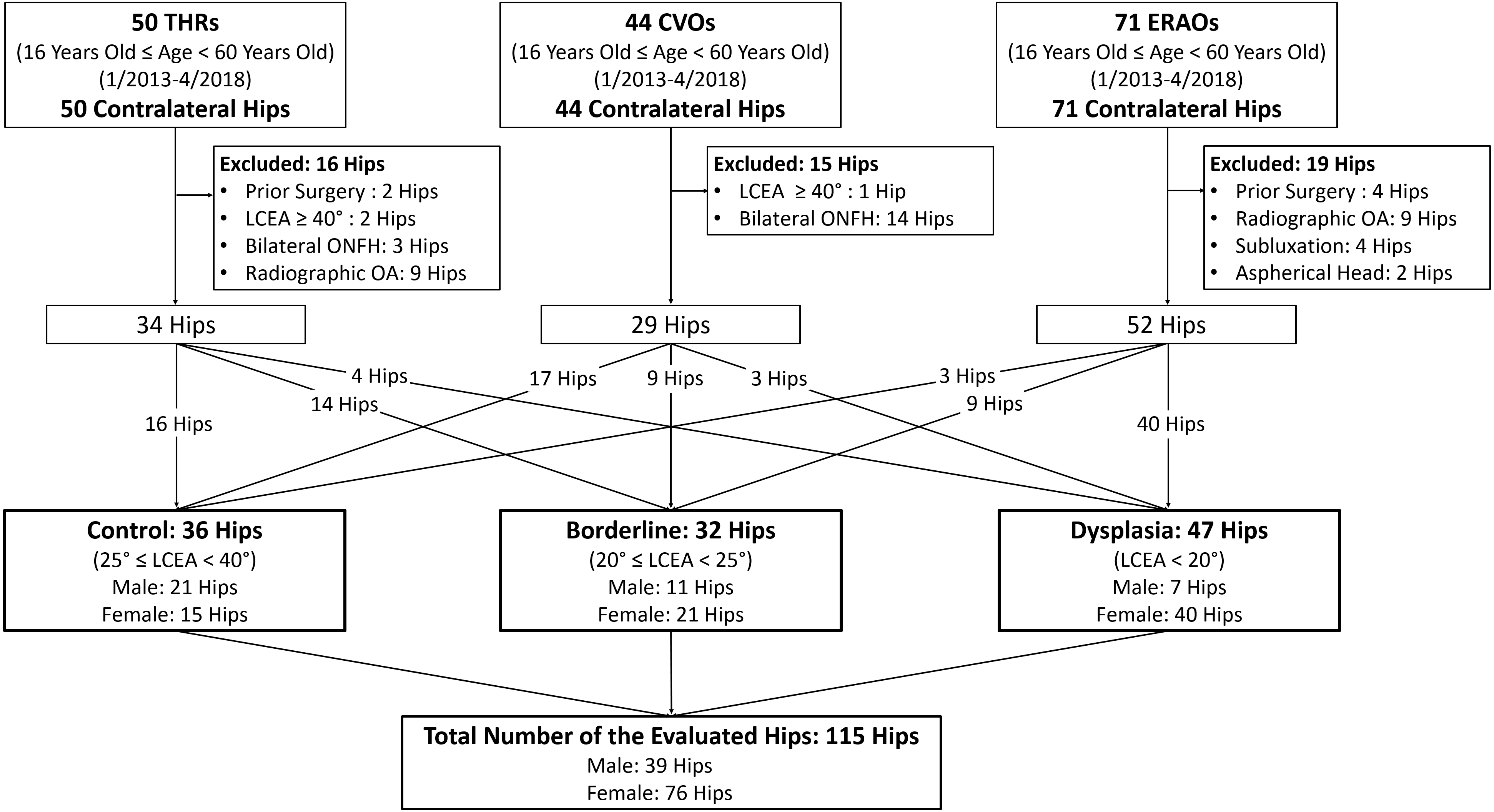
	LCEA (°)	Tönnis angle (°)	AcAV (°)
Antero-caudal (°)	r = 0.596, p < 0.001	r = -0.548, p < 0.001	r = -0.322, p < 0.001
Antero-cranial (°)	r = 0.574, p < 0.001	r = -0.514, p < 0.001	r = -0.243, p = 0.009
Supra-anterior (°)	r = 0.750, p < 0.001	r = -0.661, p < 0.001	r = -0.312, p < 0.001
Supra-posterior (°)	r = 0.608, p < 0.001	r = -0.494, p < 0.001	r = -0.206, p = 0.027
Postero- cranial (°)	r = 0.611, p < 0.001	r = -0.505, p < 0.001	r = -0.159, p = 0.091
Postero- caudal (°)	r = 0.613, p < 0.001	r = -0.554, p < 0.001	r = -0.195, p = 0.036

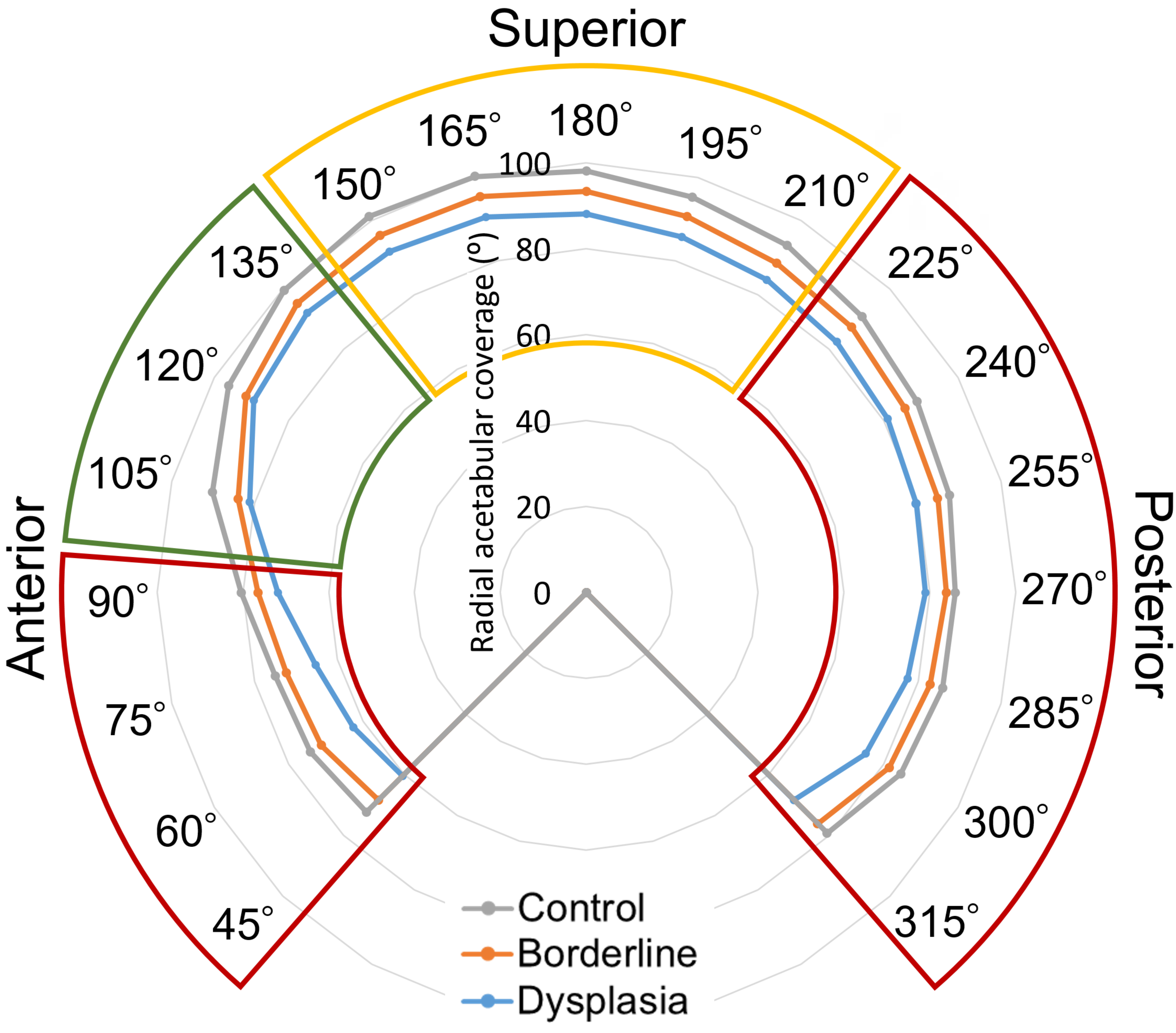
LCEA = lateral center-edge angle; AcAV = acetabular anteversion angle.


LCEA
A
Tönnis angle
B
AcAV
C



A
CFA
FHC
AIC
0°
PIC
Obturator foramen
Acetabular reference axis
B
Detected acetabular rim border points
Obturator foramen
C
Radial acetabular coverage
CFA
FHC
PIC
Obturator foramen
Acetabular reference axis
D
180°
135°
225°
Supra-anterior
Supra-posterior
Antero-cranial
Postero-cranial
Acetabular reference axis
90°
270°
CFA
Antero-caudal
Postero-caudal
AIC
PIC
Acetabular notch midpoint
45°
315°
0°
Obturator foramen


50 THRs
(16 Years Old ≤ Age < 60 Years Old)
(1/2013-4/2018)
50 Contralateral Hips
44 CVOs
(16 Years Old ≤ Age < 60 Years Old)
(1/2013-4/2018)
44 Contralateral Hips
71 ERAOs
(16 Years Old ≤ Age < 60 Years Old)
(1/2013-4/2018)
71 Contralateral Hips
Excluded: 16 Hips
• Prior Surgery : 2 Hips
• LCEA ≥ 40° : 2 Hips
• Bilateral ONFH: 3 Hips
• Radiographic OA: 9 Hips
Excluded: 15 Hips
• LCEA ≥ 40° : 1 Hip
• Bilateral ONFH: 14 Hips
Excluded: 19 Hips
• Prior Surgery : 4 Hips
• Radiographic OA: 9 Hips
• Subluxation: 4 Hips
• Aspherical Head: 2 Hips
34 Hips
29 Hips
52 Hips
16 Hips
14 Hips
4 Hips
17 Hips
9 Hips
3 Hips
3 Hips
9 Hips
40 Hips
Control: 36 Hips
(25° ≤ LCEA < 40°)
Male: 21 Hips
Female: 15 Hips
Borderline: 32 Hips
(20° ≤ LCEA < 25°)
Male: 11 Hips
Female: 21 Hips
Dysplasia: 47 Hips
(LCEA < 20°)
Male: 7 Hips
Female: 40 Hips
Total Number of the Evaluated Hips: 115 Hips
Male: 39 Hips
Female: 76 Hips



Superior
Anterior
Posterior
180°
165°
195°
150°
210°
135°
225°
120°
240°
105°
255°
90°
270°
75°
285°
60°
300°
45°
315°
Radial acetabular coverage (°)
100
80
60
40
20
0
Control
Borderline
Dysplasia


p < 0.001
p < 0.001
p < 0.001
p < 0.01
p < 0.001
p < 0.01
p < 0.01
p < 0.001
p < 0.05
p < 0.01
p < 0.001
p < 0.001
p < 0.001
p < 0.001
120
100
80
60
40
20
0
Zonal-acetabular coverage (º)
Antero-caudal
Antero-cranial
Supra-anterior
Supra-posterior
Postero-cranial
Postero-caudal
Control
Borderline
Dysplasia