Best bone of acetabulum for cup component placement in Crowe types I to III dysplastic hips: a computer simulation study

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Abstract

Background: During cup implantation, vertical height of the cup center (V-HCC) should be precisely controlled to achieve sufficient bone-cup coverage (BCC). Our study aimed to investigate the acetabular bone stock and the quantitative relationship between V-HCC and BCC in Crowe types I to III hips.

Methods: From November 2013 to March 2016, pelvic models of 51 patients (61 hips) with hip dysplasia were retrospectively reconstructed using a computer software. Acetabular height and doom thickness were measured on the mid-acetabular coronal cross section. V-HCC was defined as the vertical distance of cup rotational center to the interteardrop line (ITL). In the cup implantation simulation, the cup was placed at the initial preset position, with a V-HCC of 15 mm, and moved proximally by 3-mm increments. At each level, the BCC was automatically calculated by computer. Analysis of variance and Kruskal-Wallis test were used to compare the differences between groups.

Results: There were no significant between-group differences in maximum thickness of the acetabular doom; however, peak bone stock values were obtained at heights of 41.63 ± 5.14 mm (Crowe type I), 47.58 ± 4.10 mm (Crowe type II), and 55.78 ± 3.64 mm (Crowe type III) above the ITL. At 15 mm of V-HCC, median BCC was 78% (75–83%) (Crowe type I), 74% (66–71%) (Crowe type II), and 61% (57–68%) (Crowe type III). To achieve 80% of the BCC, the median V-HCC was 16.27 (15.00–16.93) mm, 18.19 (15.01–21.53) mm, and 24.13 (21.02–28.70) mm for Crowe types I, II, and III hips, respectively.

Conclusion: During acetabular reconstruction, slightly superior placement with V-HCC <25 mm retained sufficient bone coverage in Crowe I to III hips.

Keywords: Computer simulation; Congenital dysplasia; Hip; Three-dimensional image; Total-hip replacement

Introduction

Total-hip arthroplasty (THA) is the standard, efficacious treatment for advanced degenerative arthritis in patients with congenital dysplasia of the hip (CDH).[1] Wide variability in dysplastic acetabulum deficiencies brings challenges for THA in patients with CDH.[2] Dysplastic hips can be classified by Crowe classification, which can also predict surgical complexity and the likelihood of complications.[3]

In severe cases of CDH, acetabular reconstruction is technically demanding because of shallow acetabular concavity, anterolateral bone deficiencies, and osteophytes.[4] While the debate on optimal cup position and reconstruction strategies is ongoing, many have asserted that placement of acetabular components in "an anatomic position," by placing the hip center as medially and inferiorly as possible, is necessary for optimizing the biomechanical environment.[5] However, for a cementless cup, this process may cause the bone-cup coverage (BCC) less than 75% to 80%, which is against the biologic fixation.[6]

Upward placement of the cementless cup component may allow for better bone stock than "an anatomic position," especially in Crowe type II or III hips.[7] Recent reports have shown satisfactory long-term outcomes in dysplastic hips treated with a superiorly placed cementless acetabular component.[8,9] However, high hip center is still a controversial topic. Komiyama *et al* reported that a higher hip center was a risk factor for dislocation,[10] delayed recovery of abductor muscle moment, and lower ranges of flexion and internal rotation after THA.[11]

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The combined positive and negative results of the superiorly placed cementless components are intriguing. For cup implantation in a dysplastic acetabulum, the vertical height of the cup center (V-HCC) should be carefully and precisely controlled, not only to achieve sufficient BCC, but also to avoid excessive superior placement. In this context, we present a novel three-dimensional (3D) morphologic measurement method for evaluating the bone stock of the dysplastic acetabulum and to investigate the relationship between the V-HCC and BCC in Crowe types I to III hips using computer simulation software.

Methods

Ethical approval

The study was conducted in accordance with the *Declaration of Helsinki* and was approved by the Ethics Committee of First Affiliated Hospital of Sun Yat-sen University (No. ICE[2018]283). Informed written consent was obtained from all patients prior to their enrollment in this study.

Patients

From November 2013 to March 2016, a total of 236 patients with dysplastic acetabulum admitted to our institution and underwent primary cementless THA surgeries were reviewed retrospectively. Dysplastic hips all demonstrated a lateral center-edge (CE) angle of <20° on anteroposterior (AP) pelvic radiographs. By priori power analysis using G* power (UCLA, USA), an estimated 33 cases in total would be needed to provide 95% power of analysis of variance (ANOVA) test, with two-sided α of 0.05. Of the 236 patients, we excluded 178 (204 hips) without standard computed tomography (CT) scans, 5 (8 hips) that were graded as Crowe type IV, and 2 (4 hips) with Legg-Calve-Perthes-like deformities. Thus, a total of 51 patients (61 hips) were included, 10 of whom had bilateral involvement and 41 with unilateral hip involvement. According to the Crowe classification system, 25 were Crowe type I, 20 were Crowe type II, and 16 were Crowe type III. The Crowe classification was evaluated through plain radiograph [Figure 1]. The demographic data are shown in Table 1.

CT scan and 3D reconstruction protocol

Hip CT scans were performed on all patients. The patients were placed in a supine position. All scans included the anterior superior iliac spine and proximal femur, obtained with a 0.5- to 0.8-mm slice thickness and 0.459 to 0.912 mm pixel dimensions using a Toshiba Aquilion CT scanner (120 kVp, 320 mA, 512 × 512 matrix, Toshiba, Japan). Imaging data were exported in Digital Imaging and Communications in Medicine format and transferred to a computer for 3D reconstruction using BOHOLO software (Fengsuan Ltd., Shanghai, China). This software allows the use of cup component placement THA planning. We used a threshold of 226 to 3071 Hounsfield Units for bone density to extract the skeletal portions of the CT image, and a 3D pelvis model was separately reconstructed in each case. Figure 1 shows the two-dimensional (2D) plain radiograph and 3D structure of Crowe types I to III dysplastic acetabulum.

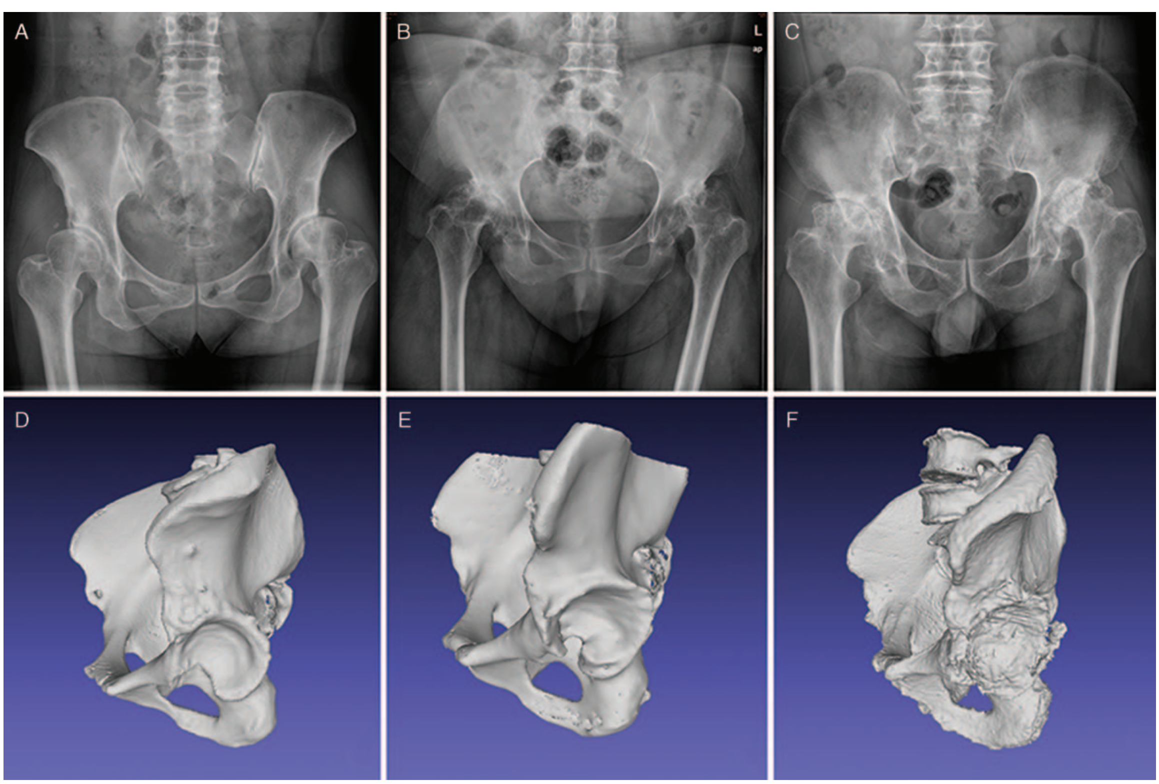

Figure 1: Plain radiograph and 3-dimensional reconstruction of Crowe types I to III dysplastic hips. (A, D) show Crowe type I hips, (B, E) show Crowe type II hips, and (C, F) show Crowe type III hips.

Table 1: Demographic data of the patients with dysplastic acetabulum.

Crowe classification	Hips (No.)	Males/females (No. of hips)	Age* (years)	Height* (cm)	BMI* (kg/m^2)
I	25	5/20	59.84 ± 8.80	157.68 ± 6.53	23.85 ± 2.79
II	20	4/16	58.95 ± 8.70	157.70 ± 7.89	24.18 ± 2.83
III	16	6/10	57.06 ± 13.92	157.19 ± 8.51	22.95 ± 1.77
Total	61	15/46	58.82 ± 10.23	157.56 ± 7.41	23.72 ± 2.58

*The values are expressed as the mean and the standard deviation. BMI: body mass index.

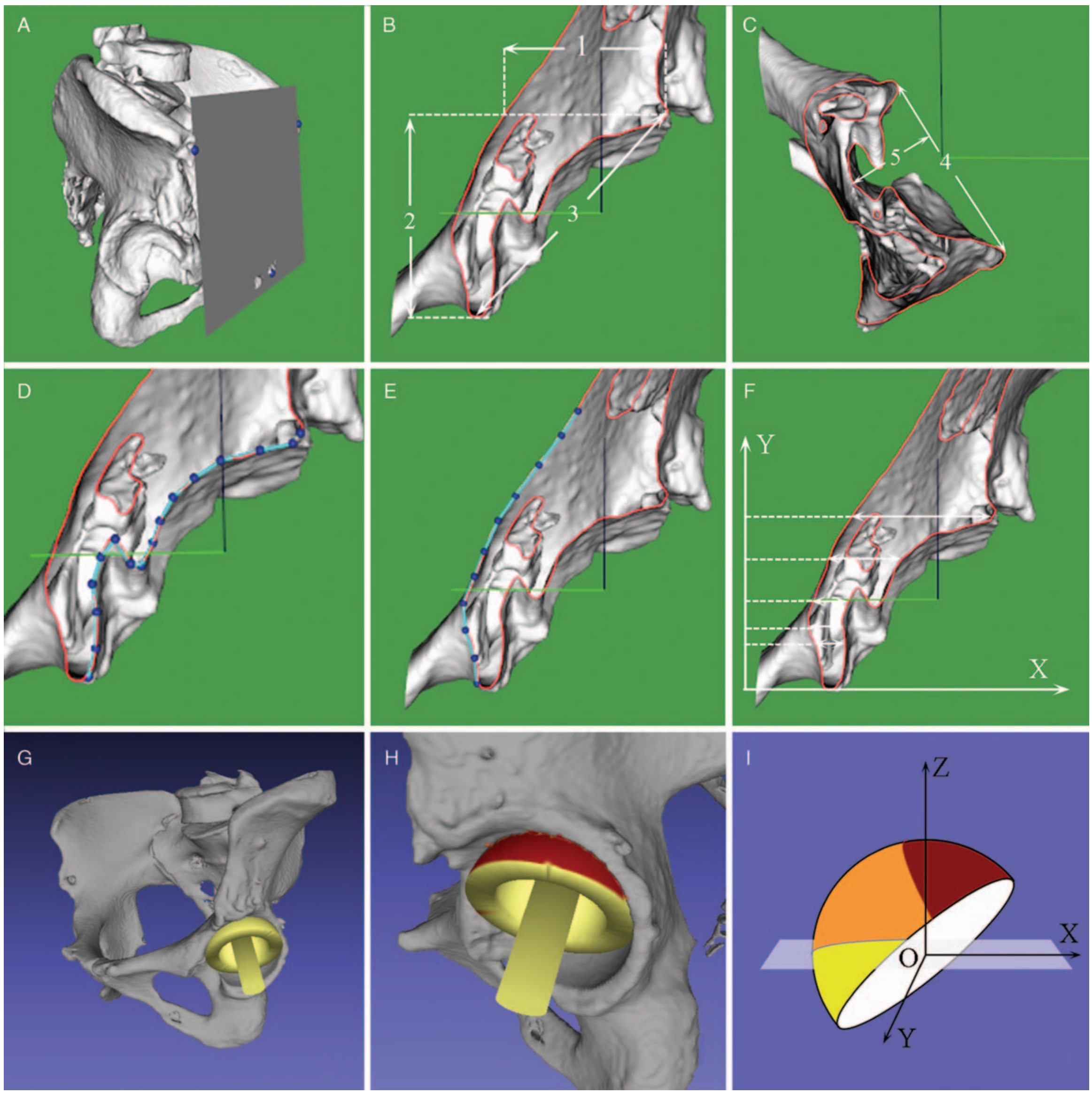

Figure 2: Acetabular morphology measurement and simulating implantation of the cup component. (A) Align the pelvis on the anterior pelvic plane (APP). (B) Measurements on the mid-coronal section: 1. Acetabular roof bone stock; 2. Acetabular height; 3. Superioinferior diameters. (C) Measurements on the mid-horizontal section; 4. Anterioposterior diameter; 5. Acetabular depth. (D, E) Polyline outlines of the cortical bone of the acetabulum were drawn on the mid-coronal section. (F) Calculation of the medial wall thickness at 0.5 mm intervals above the anatomic ITL. (G) Simulation of the cup placement (Inclination = 40°; Anteversion = 15°). (H) The uncovered area on the cup (red color). (I) Calculation of the cup coverage. Surface area of the covered portion over the surface of superior portion of the virtual cup (orange color)/total surface area of the superior portion of virtual cup (red color + orange color) × 100%.

Acetabular morphology evaluation and measurement

3D pelvis models were imported into a home-developed software in stereolithographic (STL) format. Before measurement, the anterior pelvic plane (APP) of the pelvic model was manually identified and aligned on the coronal plane and defined as the standard neutral position of the pelvis [Figure 2A]. The acetabular outer rim was identified by manually drawing a series of dots, prior to fitting the rim to a quasi-circular curve. The lengths of its superoinferior diameter and AP diameter were recorded. The mid-coronal and mid-horizontal cross sections that passed through the central point of the acetabular rim were automatically obtained. We assessed the bone stock distribution on the acetabular mid-coronal cross section. Polyline outlines of the cortical bone were drawn manually, and acetabular wall thickness was measured at 0.5 mm intervals above the anatomic interteardrop line (ITL). The maximum thickness of the level of the acetabulum dome was recorded. The height of the acetabulum was defined as the perpendicular distance from the ITL to the top of the acetabular doom [Figure 2B–F].

Simulating implantation of the prosthetic acetabular component

The 3D pelvis models were imported into BOHOLO software in STL format for cup implantation simulation. We selected the acetabular component sized to best accommodate the distance between the osseous peak of the anterior and posterior bone columns in the acetabular mid-axial section, with a V-HCC of 15 mm.[11] The outer diameters of the cup components ranged from 44 to 56 mm in 2 mm intervals. The V-HCC was defined as the vertical distance from the center of the cup component to the ITL. The simulated acetabular implantation was performed by placing the cup component at the initial preset position, with a V-HCC of 15 mm,[12] a cup inclination of 40°, and an anteversion of 15°. Thereafter, the cup was stepwise moved proximally by 3 mm increments. V-HCC ranged from 15 to 39 mm. At each level, the cup was placed as medially as possible, and the inner cortex of the medial acetabular wall was set as the medial limit for cup placement. The host BCC ratio was automatically calculated at each level by computer, using the following formula: (surface area of the covered portion over the surface of superior portion of the virtual cup/total surface area of the superior portion of virtual cup) × 100% [Figure 2 G–I]. The cup component was divided into an upper, dome-shaped portion and a lower portion by using a transverse plane passed through the cup center. All evaluations and morphologic measurements were performed by a single senior surgeon.

Statistical analysis

After verifying the normal distribution of the data using the Shapiro-Wilk test, the data from the different Crowe groups that had a normal distribution were expressed as mean ± standard deviation, and they were compared using the one-way analysis of variance (ANOVA) test, followed by the least significant difference method for pairwise comparisons. For non-parametric data, they were expressed as median (Quartile), and Kruskal-Wallis test was used to compare the differences in Crowe I to III groups, followed by Mann-Whitney *U*-test with Bonferroni correction for pairwise comparisons. All statistical analyses were performed using SPSS version 22.0 software (IBM, New York, NY, USA), and a *P*-value of <0.05 was considered significant.

Results

Morphologic analysis

For Crowe types I, II, and III hips, the average bone stock distribution on the acetabular mid-coronal cross section is shown in Figure 3. The maximum thickness of the acetabular roof bone stock was 44.15 ± 6.75 mm in Crowe type I hips, 43.99 ± 6.29 mm in Crowe type II hips, and 38.81 ± 7.73 mm in Crowe type III hips. There were no significant between-group differences among Crowe types I to III hips ($F = 1.250$, $P = 0.294$). The height of the acetabulum in Crowe type III hips was significantly larger than Crowe type I (55.78 *vs.* 41.63 mm, $t = -9.569$, $P < 0.01$) and Crowe type II hips (55.78 *vs.* 47.58 mm, $t = -6.261$, $P < 0.01$). Other morphologic features of the dysplastic acetabulum in Crowe type III hips included larger acetabular superoinferior and AP diameters [Table 2]. The measurements and selected cup component sizes for Crowe types I, II, and III hips are detailed in Table 2 and illustrated in Figure 2.

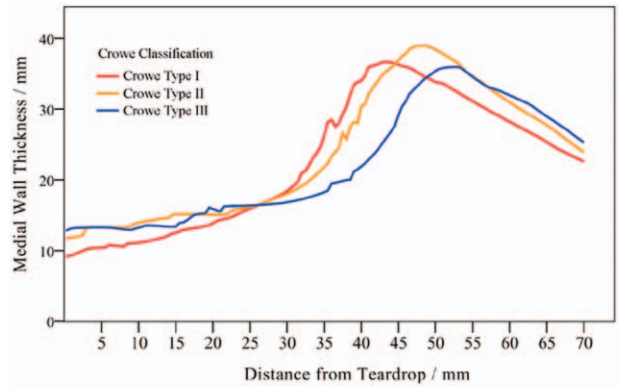

Figure 3: The average bone stock distribution on the acetabular mid-coronal cross section for Crowe types I, II, and III hips.

Host BCC ratio vs. the height of the cup center from the ITL

For Crowe types I, II, and III hips, the host BCC ratio *vs.* the height of the cup center from the ITL is shown in Table 3 and Figure 4. During the simulation study, the diameter of the cup was 48.48 ± 1.85 mm, 49.00 ± 1.37 mm, and 49.88 ± 1.71 mm for Crowe types I, II, and III hips, respectively. At the initial cup center position, which was 15 mm above ITL, the median host BCC was 78% (75–83%) (Crowe type I), 74% (66–71%) (Crowe type II), and 61% (57–68%) (Crowe type III). To achieve 80% of the coverage, the median V-HCC was 16.27 (15–16.93) mm, 18.19 (15.01–21.53) mm, and 24.13 (21.02–28.70) mm for Crowe types I, II, and III hips, respectively. The coverage ratios increased to peak values of 97% (94–98%) at 21 to 24 mm above the ITL (Crowe type I), 96% (94–98%) at 24 to 27 mm above the ITL (Crowe type II), and 90% (82–95%) at 30 to 33 mm above the ITL (Crowe type III).

Discussion

This 3D computer simulation study of cup component placement in patients with Crowe types I to III dysplastic hips demonstrated that V-HCC <25 mm retained sufficient bone coverage. By 3D morphologic analysis, our study also shown that acetabular bone stock correlates with the degree of hip dysplasia.

Table 2: Measurement of the morphologic parameters.

Parameters	Crowe I ($n=25$)	Crowe II ($n=20$)	Crowe III ($n=16$)	ANOVA*	I *vs.* II*	II *vs.* III*	I *vs.* III*
Height (mm)	41.63 ± 5.14	47.58 ± 4.10	55.78 ± 3.64	–†	–†	–†	–†
Roof bone stock (mm)	40.25 ± 5.47	42.17 ± 6.45	38.81 ± 7.73	0.301	0.322	0.124	0.487
Anteroposterior diameter (mm)	48.76 ± 3.73	49.37 ± 2.95	48.43 ± 5.65	0.773	0.620	0.498	0.807
Superoinferior diameter (mm)	60.21 ± 5.01	68.09 ± 4.52	73.26 ± 5.50	–†,‡	–†	–†	–†
Depth (mm)	17.54 ± 3.84	15.96 ± 3.07	13.55 ± 3.95	–†	0.152	0.053	–†

– indicates that $P < 0.05$ and $P < 0.01$. * One-way ANOVA test was used to compare the differences in Crowe I to III groups, followed by the least significant difference method for pairwise comparisons. † $P < 0.01$ for the comparison between the Crowe I to III groups. ‡ $P < 0.05$, which shows the significant inter-group differences. ANOVA: Analysis of variance.

Table 3: Host bone-cup coverage with increased vertical height of the cup center in Crowe types I to III hips.

	BCC (%)						
V-HCC (mm)	Crowe I ($n=25$)	Crowe II ($n=20$)	Crowe III ($n=16$)	K-W test*	I *vs.* II*	II *vs.* III*	I *vs.* III*
15	78 (75–83)	74 (66–81)	61 (57–68)	–†	0.273	–†	–†
18	86 (83–89)	79 (74–87)	68 (61–71)	–†	–‡	–†	–†
21	92 (89–95)	87 (79–92)	74 (67–79)	–†	–‡	–†	–†
24	95 (89–98)	91 (84–94)	79 (73–84)	–†	0.450	–†	–†
27	91 (83–96)	90 (88–95)	86 (76–89)	0.077	1.000	–‡	0.396
30	79 (72–92)	90 (84–96)	84 (80–90)	0.056	0.108	0.231	0.849
33	71 (62–81)	83 (73–91)	80 (74–89)	0.072	0.147	1.000	0.189
36	63 (58–77)	75 (67–83)	75 (67–83)	0.114	0.249	1.000	0.240
39	61 (52–70)	69 (58–77)	67 (61–74)	0.129	0.249	1.000	0.303

Data were shown as median (interquartile range). * Kruskal-Wallis test was used to compare the differences in Crowe I to III groups, followed by Mann-Whitney U test with Bonferroni correction for pairwise comparisons. † $P < 0.01$ for the comparison between the Crowe I to III groups. ‡ $P < 0.05$, which shows the significant inter-group differences. V-HCC: Vertical height of the cup center; BCC: Bone-cup coverage.

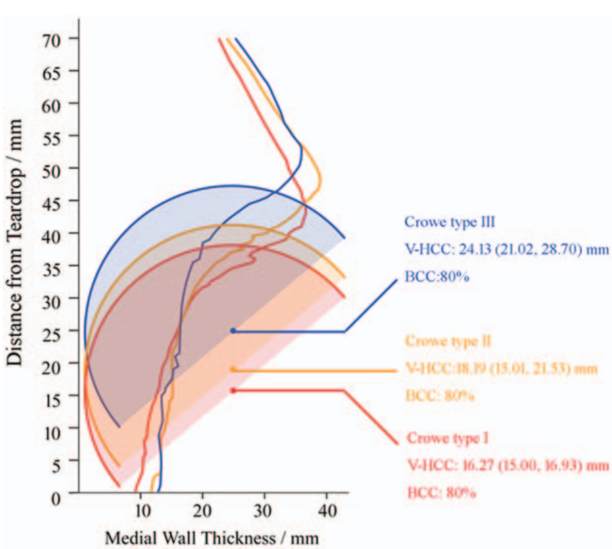

Figure 4: Medial wall thickness, the height of the cup center from the ITL, and the host-bone coverage in Crowe types I to III hips. BCC: Host bone-cup coverage; V-HCC: Vertical height of the cup center to the ITL; ITL: Interteardrop line.

The present study had limitations. The first limitation is the small number of subjects in the Crowe type III group. Second, no normal hips were included. Patients with normal acetabula did not all undergo CT scans for THA; however, normal morphologic parameters were obtained from the literature. Third, in this simulation study, cup inclination, and anteversion were fixed, and all cups were fully medialized to make full use of the medial bone stock and prevent cup protrusion. This process minimized potential confounding factors related to bone coverage. However, in surgical situations, factors like medialization or varying inclinations may produce different results. Our results should be interpreted in light of this fact.

Sufficient host bone coverage is crucial for reliable cup fixation. Previously reported minimum bone coverage is 50% to 75%.[13-15] This wide variation could be explained by discrepancies between 2D and 3D coverage and different surgery-related factors. Tikhilov *et al* showed that cup implantation with more than 75% bone coverage should theoretically achieve primary stability without screw fixation through the finite element method and mechanical experimentation.[6] Due to the highly sloped acetabular roof of the dysplastic hip, the surgeon may believe that inferior placement of the hip center may produce insufficient host bone coverage and compromised initial cup stability. High cup component placement was necessary for sufficient bone coverage. However, this surgical technique also introduces the possibility of over-elevation.[5,16,17] Our results showed that a V-HCC of 15 mm retained host BCC by 78% (75–83%) in Crowe type I hips, 74% (66–71%) in Crowe type II hips, and 61% (57–68%) in Crowe type III hips. Even if the bone coverage was set to 80%, the V-HCC was 16.27 (15.00–16.93) mm for Crowe type I hips, 18.19 (15.01–21.53) mm for Crowe type II hips, and 24.13 (21.02–28.70) mm for Crowe type III hips. Past studies indicated that a V-HCC <25 mm was associated with long-term implant survival, lower joint dislocation risk, early recovery of abductor muscle moment, and establishment of an impingement-free range of joint motion.[9-11,18]

Recent clinical reports have shown excellent outcomes in dysplastic hips treated with slightly superiorly placed cementless and cemented cup components, especially when medialization is applied. Li *et al* reported no cases of aseptic loosening at a mean follow-up of 5 years in 52 patients with CDH, 47 of whom were Crowe type II or III hips, with a mean V-HCC of 21 mm, even though the 2D uncoverage ratio was between 30% and 50%.[19] However, there was a significant discrepancy and a fair correlation between 2D and 3D coverage in patients with CDH. The 2D measurement underestimated 3D coverage by 13%.[7] Given this discrepancy, some cups with low 2D coverage had sufficient 3D coverage for cup fixation. In the current study, at a mean V-HCC of 21 mm, the 3D coverage could retain 87% (79–92%) in Crowe type II hips and 74% (67–79%) in Crowe type III hips, consistent with Zhu's study. Similarly, Nawabi *et al* also reported no cases of aseptic loosening at a mean follow-up of 12 years. The mean V-HCC was 17.3 mm in Crowe type I hips, 25.6 mm in Crowe type II hips, and 30.3 mm in Crowe type III hips.[20] Additionally, Kaneuji *et al* reported clinical outcomes following cementless THA in patients with Crowe types I to III hip dysplasia. The mean V-HCC was 21.8 ± 1.3 mm in Crowe type I hips, 28.2 ± 3.4 mm in Crowe type II hips, and 32.3 ± 5.6 mm in Crowe type III hips. There were no acetabular failures at a minimum of 10 years.[21] In these two clinical studies, the authors sought to achieve host bone coverage >75%, while the hip center heights were maintained within an acceptable range. However, among different Crowe groups, hip centers were placed about 5 to 10 mm higher than those in the current study. It is possible that the acetabular reaming may not be fully medialized or the surgeons may underestimate the actual bone coverage during the operation. Surgeons will naturally tend to upwardly file the acetabulum to obtain more sufficient bone coverage. Therefore, a 3D computer stimulation based on CT-scan images could provide accurate information pertaining to optimal cup component position and corresponding bone coverage. This could help surgeons evaluate acetabular bone stock distribution; make intraoperative decisions regarding cup size, hip center height, and additional screw fixation or bone grafts; and predict the survival of the cup component.

The bone stock of the medial acetabular wall determines the amount of cup medialization, while the bone stock of the acetabular doom determines the height at which the cup component achieves sufficient bony support. Many studies have investigated the morphology of young adults with hip dysplasia based on CT images, mostly focusing on the shape and orientation of bony defects.[22,23] However, a few studies specifically quantified the acetabular bone stock in patients with late stage osteoarthritis and hip dysplasia secondary to CDH. Yang *et al* reported that there is more bone stock in the medial acetabular wall in Crowe type II or III hips, compared to Crowe type I hips.[24] In the current study, we evaluated the bone stock distribution in the medial acetabular wall, from the bottom edge to the acetabular roof, in Crowe types I, II, and III hips. There were no significant between-group differences in maximum thickness of the acetabular roof; however, peak bone stock values were obtained at heights of 41.63 ± 5.14 mm (Crowe type I), 47.58 ± 4.10 mm (Crowe type II), and 56.55 ± 3.56 mm (Crowe type III) above the ITL.

In summary, in patients undergoing THA secondary to CDH, the bone stock distribution of the acetabulum, which varies according to dysplasia severity, should be taken into account when reaming the socket during acetabular reconstruction, slightly superior placements, with V-HCC <25 mm, retained sufficient bone coverage.

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Conflicts of interest

None.

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