A New Method to Evaluate Acetabular Bone Defect in Patients With Crowe Type Ⅲ and Type Ⅳ Developmental Dysplasia of the Hip: Acetabular Reconstruction Based on Three-dimensional Reconstruction Images

Xinggui Wen
China-Japan Union Hospital of Jilin University
Jianlin Zuo
China-Japan Union Hospital of Jilin University
Tong Liu
China-Japan Union Hospital of Jilin University
Zhongli Gao
China-Japan Union Hospital of Jilin University
Jianlin Xiao (xiaojianlin10@jlu.edu.cn)
China-Japan Union Hospital of Jilin University

Research Article

Keywords: Developmental dysplasia of the hip, Acetabular reconstruction, High hip center technique, Bone defects distribution map

Posted Date: June 1st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-557768/v1

Abstract

This study evaluated the cup coverage(CC) of acetabular cup models with different sizes in patients with Crowe type □ and type □ DDH by the high hip center technique(HHC), the results shows that the CC of cup sizes with 38mm, 40mm, 42mm, 44mm, 46mm, 48mm, and 50 mm increased by 21.24%, 21.58%, 20.86%, 20.04%, 18.62%, 17.18%, and 15.42% ($P<0.001$) respectively as the cups elevated from the true acetabula until the maximum coverage were achieved. What surprising is the mean CC at the true acetabula were 77.85%, 76.71%, 75.73%, 74.56%, 73.68%, 72.51%, and 71.75%, respectively.

So, we draw a distribution frequency map of uncovered portion of all 44-mm cups at the true acetabula to illustrate the distribution of bone defects of the acetabulum. The map shows that 95% of type □ and type □ DDH acetabula had bone defects in posterosuperior, and 60% were located outside the force line of the hip joint.

Here comes to a conclusion that acetabular cups can meet the CC of more than 70% at the true acetabulum, and 60% of Crowe type □ and type □ DDH patients can obtain satisfactory CC at the true acetabulum by using a 44-mm cup without additional operation.

Introduction

The best approach for placement of the acetabular component in total hip arthroplasty (THA) remains controversial for patients with developmental dysplasia of the hip (DDH), especially for those with Crowe type □ and type □. When the acetabular cup is placed at the level of the true acetabulum, the bone defect caused by acetabular dysplasia may result in poor cup coverage (CC) in THA[1, 2], thus leading to unsatisfactory initial stability and low long-term survival rate[3–5]. In order to achieve adequate CC, several studies[6–8] have recommended bone grafting, the medial protrusio technique, and the use of extra-small cups at the true acetabulum to during acetabular reconstruction. However, it remains disputable whether these techniques are helpful for reconstructing the acetabulum in DDH patients, because these techniques have various complications and uncertain long-term survival rates[9–11].

The high hip center (HHC) technique placing the acetabular cup above the true acetabulum during acetabular reconstruction, is suitable for DDH patients, because it can make full use of the bone above the true acetabulum to ensure adequate host bone coverage of the cup[12, 13]. In addition, the HHC technique is also associated with some advantages such as reduced additional surgery and shortened operation time[13]. Based on three-dimensional (3D) reconstruction technology, several studies have shown that the HHC technique can greatly increase the bone coverage of the cup[14–16], that may result in significant increases in the initial stability of the cup, bone ingrowth, and long-term survival. Our previous study on morphological features of the true acetabulum in DDH patients shows that the bone stock at the true acetabulum of Crowe type □ and Crowe type □ patients was sufficient to support acetabular reconstruction, but for type □ and type □ patients, additional surgery may be required for in situ acetabular reconstruction[17]. However, these studies did not conduct in-depth study on acetabular reconstruction evaluation of type □ and type □ DDH.

In 2009, Armitage et al[18]. analyzed the distribution of fracture line with 3D CT of scapula, and proposed the concept of fracture map. In the recent years, many studies reported the analysis of different fracture maps[19–21]. To our knowledge, there is no study introduce the concept of fracture map into the field of joint replacement and related research, and investigate the distribution of acetabular bone defects in patients with type □ and type □ DDH from the perspective of uncovered acetabular cup.

Since a 44-mm cup is the smallest one available for ceramic-ceramic cementless prosthesis, some studies regard 44 mm cup as a standard cup[15, 16]. In the present study, we firstly evaluated the CC of acetabular cup models with different sizes in patients with Crowe type □ and type □ DDH using the HHC technique to reconstruct the acetabulum, then analyzed the CC of host bone in all hips when reconstructing acetabulum at the true acetabulum with 44-mm acetabular cup models. Finally, evaluated the uncoverage of cup models with 44-mm diameter at the true acetabulum, and draw a 3D distribution map of the uncovered portions of the acetabular cup that can represent the bone defect of the true acetabulum.

Materials And Methods

Patients

This study was approved by the Institutional Review Board, Ethics Committee of China-Japan Union Hospital (IRB No: 2016ks001). All patients had signed informed consent before X-ray and computer tomographic (CT) examination. All operations and experiments were carried out in strict accordance with the relevant regulations and guidelines. The present study included 49 hips of 39 patients (3 males and 36 females) who underwent hip X-ray and CT examination in our hospital. According to Crowe classification[1], 28 hips were classified as type □, and 21 hips were type □. All patients did not have hip diseases including avascular necrosis of femoral head and infection or history of hip surgery, such as pelvic osteotomy, bone grafting, and osteotomy of the femur. The demographic data are shown in Table 1.

Table 1
Demographic characteristics

Characteristic	Value
Number of patients (hips)	39 (49)
Gender (male/female)	3/36
Age (Years) □	48.92 ± 10.69
Height (cm) □	158.59 ± 5.78
Weight (kg) □	60.74 ± 9.65
BMI (Body Mass Index, kg/m^2) □	24.11 ± 3.38
Unilateral(left/right)	29(12/17)
Bilateral	10
Crowe type (number of hips)	
□	28
□	21
□ Values are expressed as means ± SD.	

CT scan and 3D reconstruction

CT scans of the entire pelvis were performed by Toshiba Aquilion CT scanner (120 kVp, 320 mA, 512×512 matrix, and 0.5-mm slice thickness). All CT data were saved in Digital Imaging and Communications in Medicine (DICOM) format, then imported into Mimics 17.0 software (Materialise) and used to reconstruct 3D images for each pelvis. The position of 3D reconstruction images were adjusted according to the anterior plane of the pelvis determined by the anterior superior iliac spine and pubic tubercle[17].

Simulating Implantation of the Acetabular Cup Model

We used a set of acetabular cup models created in our previous study[17]. The diameter of the cups ranged from 38–50 mm in 2-mm increments. All cups had a shell thickness of 0.1 mm. These models were imported into the Mimics software in the STL (stereolithography) format, and the total surface area (S_t) was available. The cups were implanted into the reconstructed 3D images of the pelvis using the Mimics software, and the method of simulating acetabular cup implantation in THA was mentioned in our previous study[17]. The position of all the cups was set at 40° abduction and 15° anteversion constantly (Figure. 1A).

Measurement of CC

To measure CC, the cups were placed at the true acetabulum firstly[22], and then elevated upward in 2-mm increments until it reached 50 mm (Figure. 1B). At each elevation, the cup models were slightly adjusted on coronal and transverse sections to achieve the max CC. After the cup models were placed in the 3D reconstruction image of the pelvis, the surface area of uncovered portion (S_u), can read by the Boolean operation function of Mimics. The CC of cups with different diameters (range from 38 mm to 50 mm) at each elevation was calculated by the following formula:

$$\mathbf{CC} = (S_t - S_u)/S_t \times 100\%$$

Mapping the Uncovered Portions of Acetabular Cups

The uncovered portions of all 44-mm cups at the true acetabula were imported into Magics 22.03 software (Materialise) in STL format to overlap onto a complete cup model. Uncovered portion of all 44-mm cups were superimposed to create a compilation of uncoverage on a complete cup model serving as a representation of the exposed portion of acetabular cups in THA. The overlap of all uncoverage of cups were suited to build a distribution map of frequency based on the density of uncovered portion of cups, and then calculated the distribution frequency.

Analysis of defect distribution

Making a vertical line through the rotation center of the cup, and then built a plane perpendicular to the anterior plane of pelvis based on this line. So that, the distribution frequency of the uncovered portion of the cups outside the gravity line of hip joint can be calculated. And we can calculate the probability of taking additional surgery such as bone graft in acetabular reconstruction at the true acetabulum in patients with Crowe type □ and type □ DDH.

Statistical Analysis

All data are expressed as means ± standard deviation (SD). The paired t test was used to evaluate the differences between the CC at the true acetabulum and the maximum CC. Pearson's correlation coefficient was used to evaluate the correlation between CC and the elevated height of the cup. All statistical analyses were performed using SPSS 21.0 software (SPSS, Chicago, IL, USA). Statistical significance was defined as $P < 0.05$.

Results

The CC of all cups with different sizes at the true acetabulum were greater than 70%, and as the acetabular cups elevated from the true acetabulum, the CC gradually increased until reaching the maximum, then decreased gradually even below 70% (Fig. 2). When CC reaches the maximum and decreases to less than 70%, the corresponding elevated height of cups decreases with the increase of cup size.

CC of all cups at the true acetabulum are greater than 71%, all the cups reached the maximum CC greater than 87% after elevating from the true acetabulum, and the maximum CC was significantly different from that at the true acetabulum (Table 2). When CC reached the mean maximum value of 93.96%, the cup was elevated up to a mean height of 23.76 mm from the true acetabulum and the CC increased by 19.28% ($P < 0.001$). The mean CC of 44-mm cups at the true acetabulum is 74.56%, and it reaches the maximum of 94.61% after elevating 24.16mm from the true acetabulum.

Table 2
The CC at the true acetabulum and the maximum CC

Cup size (mm)	CC at true acetabulum (%)	Maximum CC (%)	Difference (%)	Elevated height (mm)
38	77.85 ± 7.88	99.09 ± 2.21	21.24 ± 8.27	29.14 ± 5.85
40	76.71 ± 7.28	98.30 ± 3.07	21.58 ± 7.62	27.84 ± 5.51
42	75.73 ± 6.40	96.59 ± 4.43	20.86 ± 6.94	25.96 ± 5.77
44	74.56 ± 6.21	94.61 ± 5.67	20.04 ± 6.88	24.16 ± 6.16
46	73.68 ± 6.27	92.30 ± 7.17	18.62 ± 6.54	21.76 ± 5.83
48	72.51 ± 6.65	89.69 ± 8.51	17.18 ± 7.01	19.59 ± 6.51
50	71.75 ± 7.23	87.17 ± 9.55	15.42 ± 7.07	17.88 ± 7.12
Mean	74.69 ± 7.11	93.96 ± 7.52	19.28 ± 7.46	23.76 ± 7.22

Values are presented as mean ± SD.

$P < 0.0001$, paired t test

Figure 3 shows the relationship between the CC value and the elevated height when the cup was elevated from the true acetabulum until the mean maximum value of CC was reached. The CC values were positively correlated with elevated height for cups with the sizes of 38, 40, 42, 44, 46, 48, and 50 mm, the Pearson Correlation Coefficient were 0.9922, 0.9933, 0.9918, 0.9972, 0.9879, 0.9717, and 0.9645 respectively, indicating that the correlation between CC and elevated height was almost linear in all cups. The mean elevated height that CC reach the maximum decrease with the increase of cup size.

The exposed portion of cups mainly (> 60%) concentrated in the posterosuperior, and a small area located in the area between 11 and 12 o'clock on almost all the cups are not covered by the host bone, as shown in crimson (Fig. 4). There is 50 ~ 70% uncovered portion concentrated in the anteroinferior of cup, and surprisingly, about 10%~25% uncovered portion was in the medial of cup. Uncovered portions of several special cases make the frequency of 5%~10% concentrated in the posteromedial of cup.

As shown in Fig. 4, over 60% uncovered portion of cup was outside the gravity line of hip, so it can be inferred that when the 44-mm cup is used to reconstruct acetabulum at the true acetabulum for Crowe type and type DDH patients, there is about 40% uncovered portion of cup locate within the gravity line of hip, and these hips may require additional surgery to ensure the initial CC in THA.

Discussion

According to previous studies[1], for Crowe type and type DDH patients, it is difficult to achieve satisfactory CC when reconstructing the acetabulum due to the shallow acetabulum and bone defects. Placing the cup in the bone stock above the true acetabulum with sufficient bone mass can increase the CC and ensure the initial stability of the acetabular cup[13–16, 23]. Here, we found that elevating the cups with different sizes to 23.76mm above the true acetabulum increased the CC by 19.28% during acetabular reconstruction for patients with Crowe type and type DDH, which is consistent with the findings of previous studies[12, 14–16, 23]. In addition, the mean elevated height identified in this study meets the safety range determined by Hirakawa et al.[24], who recommended that the cup should be placed < 35 mm vertically from the interteardrop line.

Sufficient host bone coverage of the acetabular cup is required to achieve satisfactory long-term implant survival for DDH patients following THA. Many studies have demonstrated that HHC technique is a feasible method for reconstructing the acetabulum at the level of true acetabulum in DDH patients[14–16]. In this study, except for the 48-mm and 50-mm cups, other cups achieved the mean CC of greater than 90% after elevating from true acetabulum. Many studies have shown that HHC technique does not cause aseptic loosening of cups, and the outcomes after medium and long-term follow-ups are satisfactory[23, 25–28]. Therefore, we believe that the HHC technique is a valid method to reconstruct acetabulum for DDH patients.

Few studies reported the analysis of acetabular reconstruction for Crowe type and type DDH patients based on CT of pelvis and acetabular cup prosthesis model. Komiyama[29] used a cup with diameter of 50mm, and positioned the cup with an inclination of 40° and an anteversion of 20° to simulate acetabular reconstruction in 32 patients with Crowe type and type DDH, the cup center-edge (Cup-CE) angle was used to evaluate CC. The result shows that, at the anatomical hip center, the mean Cup-CE was − 4.3 ± 11.8°, 13 hips (40.6%) satisfied Cup-CE ≥ 0°, and the Cup CE angle ≥ 0° was used as the cut off value for the required bone coverage in their study, which was approximately equal to bone coverage of acetabular cup ≥ 60%. Xu et al[16]. reported acetabular reconstruction for Crowe IV DDH patients with 44-mm cup at a position of 40° abduction and 20° anteversion, the simulated mean in situ 3D CC was 78.60% (67.67%-92.51%). In 2018, Liu et al[15]. evaluated CC at the true acetabulum for 20 Crowe type DDH hips with 44mm cup model, the inclination was set to 45° constantly, and three anteversion groups with 0°, 5°, and 10° were set. The CC was 65.87% ± 7.82%, 67.77% ± 8.02%, and 68.98% ± 6.97% respectively. To our knowledge, the present stud is the first one to evaluate CC at the true acetabulum for Crowe type and DDH patients based on 3D reconstruction images and the results are different from previous views and studies, that is, using cups with diameter of 38mm, 40mm, 42mm, 44mm, 46mm, 48mm, and 50mm to reconstruct acetabulum, the cups can obtain a mean 3D bone coverage of 74.69 % at the true acetabulum. According to the existing literatures[30–32], no additional operation is required to ensure the initial stability of cups during acetabular reconstruction if CC is greater than 70%.

This study analyzed CC of 44mm cups at the true acetabulum and the distribution of uncovered portion in this study. Many existing studies[2, 14, 15, 17, 33, 34] have described the bone defect of the true acetabulum in DDH patients from the perspective of pelvic morphology, but few studies analyzed the uncoverage from the perspective of acetabular cup. We all know that setting a proper position of the acetabular cup is the only thing we can do during the THA, so it is the most important to carry out relevant research from the perspective of the acetabular cup. The present study is the first one that analyzed the uncovered portion of cups in THA and drew a map of uncovered portion of cups that represents bone defects of true acetabulum. From this map, we can intuitively see the distribution and probability of the uncovered portion of the acetabular cup. The results show that 40% of the uncovered portion of cups are located inside the gravity line of hip, we believe that if the uncovered portion of the cup is located inside the gravity line of the hip joint, hearing forces on the acetabular cup may lead to early loosening[4]. So, we can predict that about 60% of type □ and type □ DDH patients can obtain satisfactory CC without additional operation when reconstructing acetabula at the true acetabulum with 44-mm cups. This proportion is not very large, but it is really a surprising finding. That is, during acetabular reconstruction for type □ and type □ DDH patients, if careful preoperative design is carried out, in many patients, placing acetabular cup at the true acetabulum can also obtain good CC and initial stability can be ensured.

On the other hand, from the results of this study, if the acetabular bone defect is too large and bone grafting is necessary, the bone defect distribution map can be used as a guide for orthopedic surgeons to determine the location of bone grafts during preoperative design.

Conclusion

Based on the 3D reconstruction technology and surgical simulation technology, although the HHC technique can improve acetabular cup coverage of host bone significantly in patients with Crowe type □ and type □ DDH, all cups can obtain a satisfactory CC (more than 70%) at the true acetabula during acetabular reconstruction. A distribution map of the uncovered portions of the acetabular cup that can represent the bone defect of the true acetabulum was drawn, and from the map, about 60% of Crowe type □ and type □ DDH patients can obtain satisfactory CC of host bone at the true acetabula by using a 44-mm cup without additional operation.

Declarations

Authors Contributions:

XG W, JL Z and JL X conceived the article. XG W and JL Z wrote the manuscript and the figures. XG W, JL Z, and T L collected the data and designed the tables. JL Z, ZL G, and JL X performed literature search and provided valuable comments. All authors discussed the results and revised the manuscript. All authors contributed to the article and approved the final manuscript.

Conflict of interest statement：

The authors declare no competing interests.

Funding Statement:

This work was supported by the funding from the National Nature Science Foundation of Youth in China (No: 81601907)，China Postdoctoral Science Foundation (No: 2020M670863)， Natural Science Foundation of Jilin Province (No: 20200201345JC).

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Figures

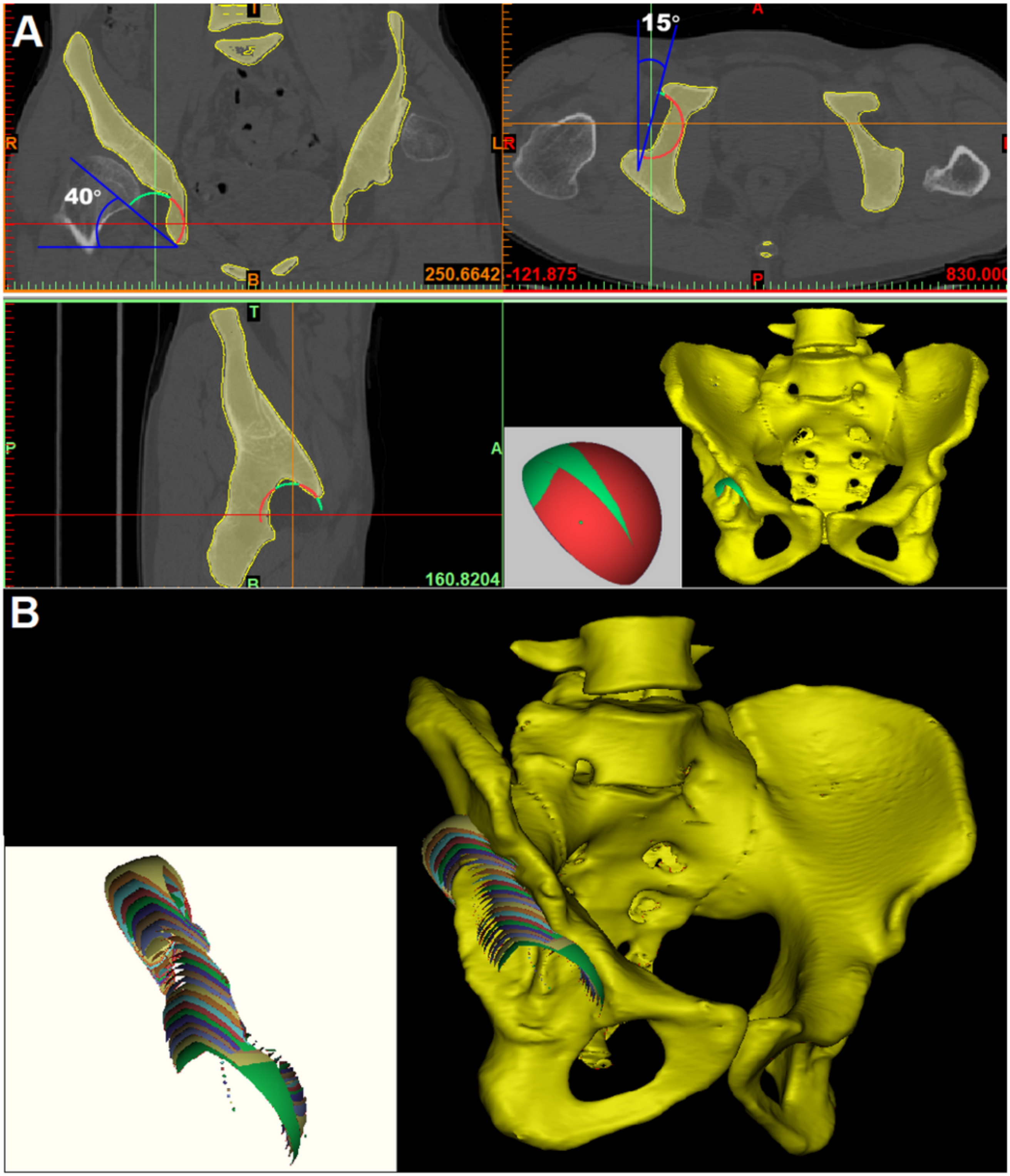

Figure 1

3D images of the pelvis reconstructed by Mimics software using complete CT data of the pelvis. A: The cup models were placed in the 3D reconstruction image of the pelvis to simulate acetabulum reconstruction in THA. The position of the cup was adjusted to 40° of abduction and 15° of anteversion on the coronal and transverse sections. The total surface area of the cup (St) can be read directly from the Mimics software. Boolean operation was used to obtain the uncovered area of cup (Su), which is indicated in green and covered area is in red. B: The uncovered portions of the cup with a diameter of 50mm at different elevations are indicated in different colors.

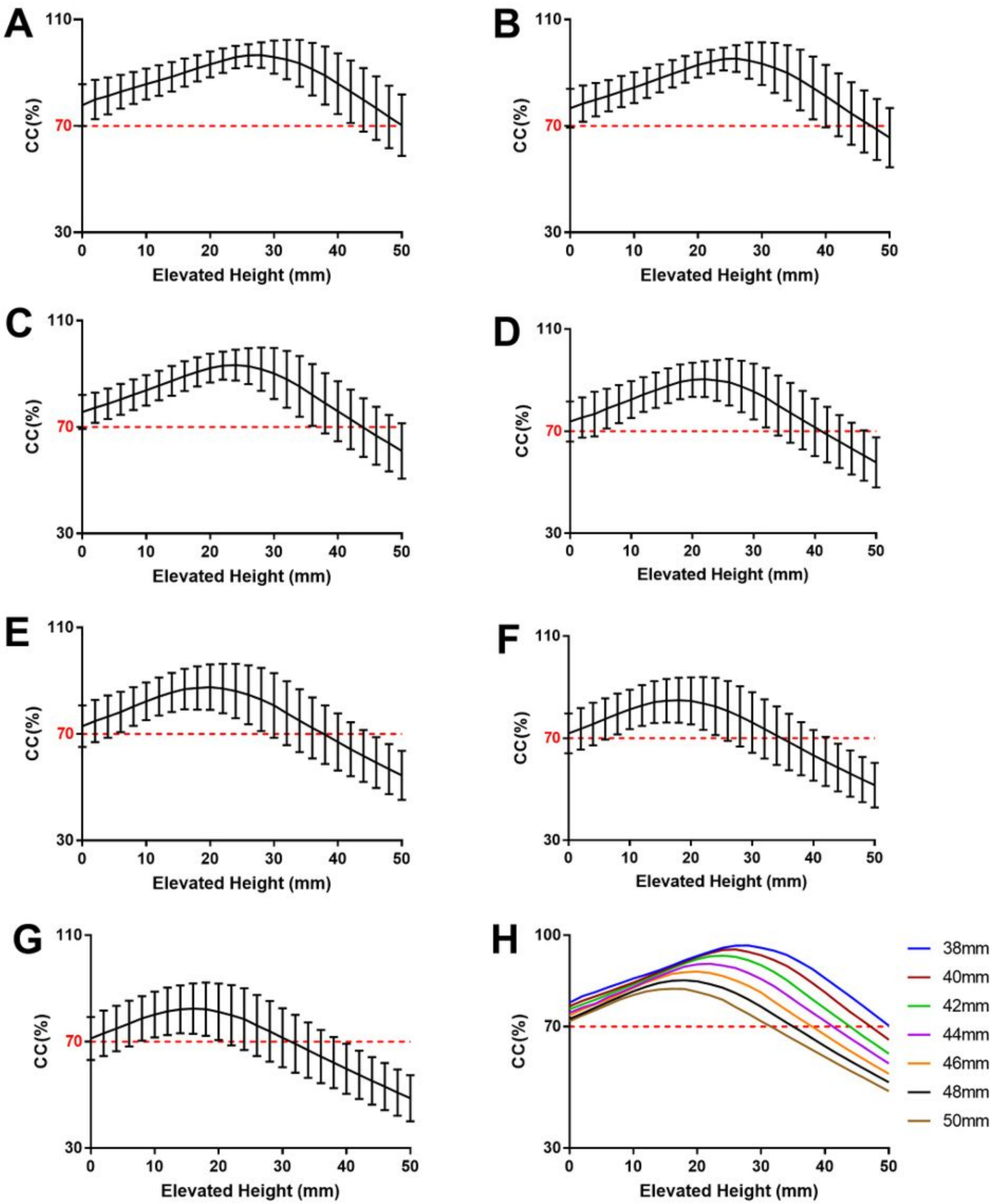

Figure 2

Changes in CC and the elevated height of the cup from the true acetabulum when for cup sizes of 38 mm (A), 40 mm (B), 42 mm (C), 44 mm (D), 46 mm (E), 48 mm (F), and 50 mm (G). H. shows the relationship between the CC and the elevated height of cups with different sizes. With the increase of cup size, the elevated height of cup decreases gradually when the maximum CC was reached.

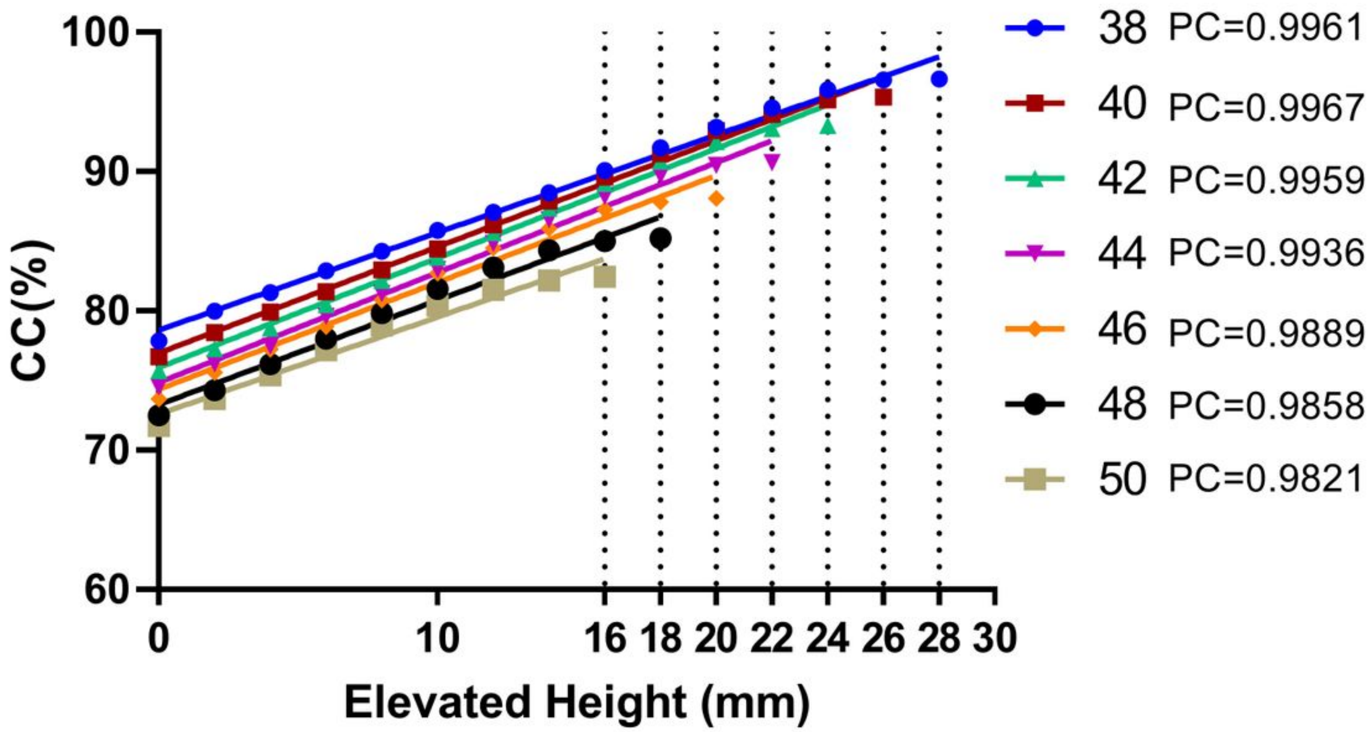

Figure 3

Relationship of the CC and elevated height of cups from the true acetabulum till the CC reached the maximum value. PC: Pearson Correlation Coefficient.

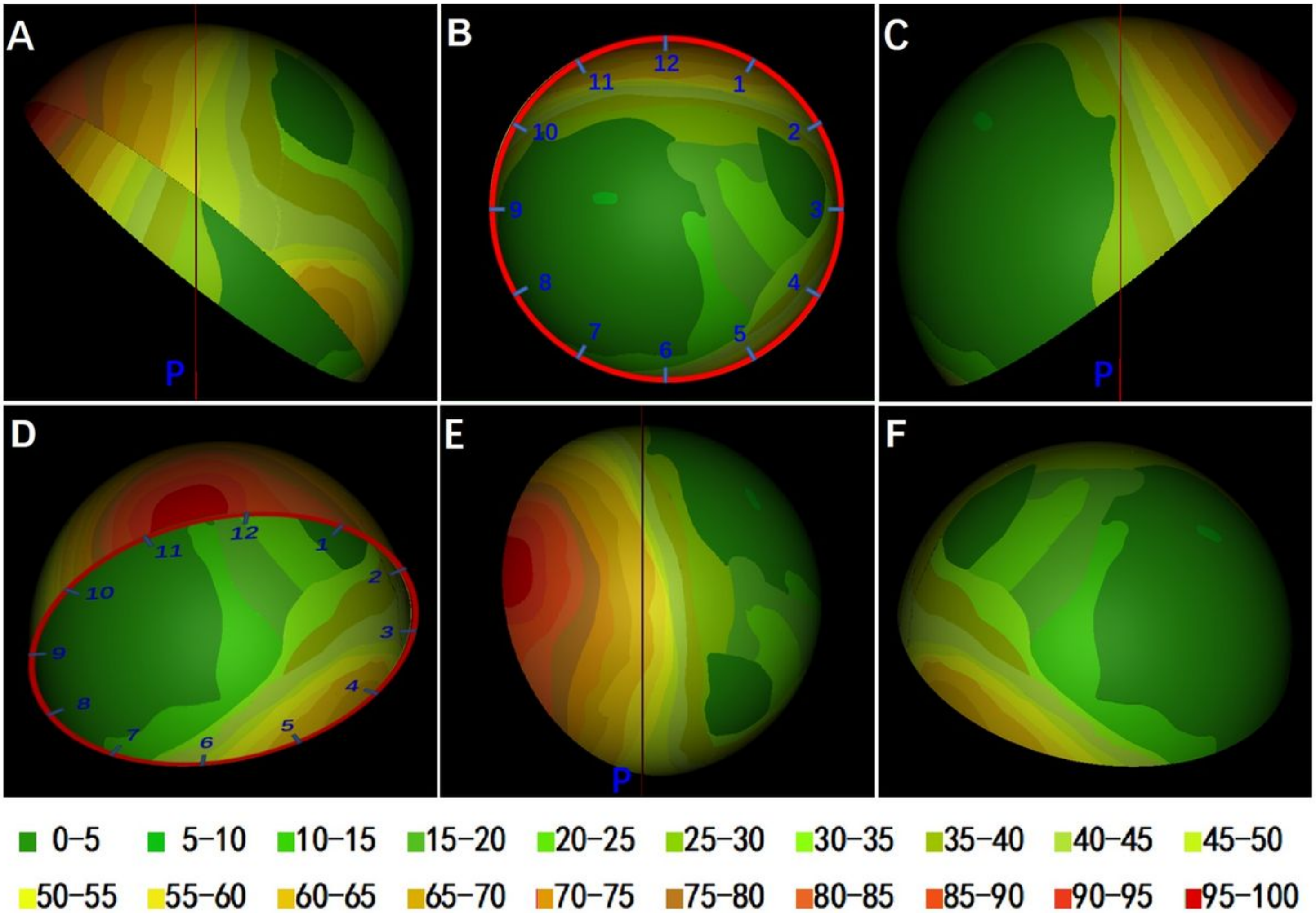

Figure 4

The distribution frequency of uncovered portion on intact cup is shown in different colors. The result is expressed as percentage with total of 49. A clock pattern was drawn on the cup to show the location of the uncovered portion. Builing a plane perpendicular to the anterior plane of pelvis through the rotation center of the cup. (A) Front view of the pelvis, the red line is a vertical line through the rotation center of the mortar cup. (B) Front view of the cup. (C) Rear view of the cup. (D) Vertical view of the cup. p: Vertical plane through the rotation center of the cup.