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ORIGINAL PAPER

A novel intraoperative acetabular reaming center locating method in total hip arthroplasty for Crowe type IV developmental dysplasia of the hip: a retrospective cohort study

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Abstract

Purpose Although the principles of hip reconstruction are consistent, due to lack of reliable anatomical landmarks, how to decide the acetabular cup reaming centre intraoperatively in Crowe IV patients with developmental dysplasia of the hip (DDH) remains unclear. This study aims to address this question.

Methods Fifty-eight Crowe IV patients were enrolled from 2017 to 2019. By examining our previous clinical data, we analyzed the anatomical morphology of Crowe IV acetabulum and proposed a method of locating intraoperative reaming centering for implantation of a standard-sized acetabular cup, which is the upper two thirds of the posterior border of the true acetabulum. All patients included in this study were reamed according to this method. The average postoperative follow-up was 4.1 years (3–5 years). The position of the centre of rotation (COR), cup coverage (CC), and optimal range of joint motion (ROM) were examined by 3D computer simulation measurement. Postoperative complications and hip Harris score were collected and analyzed.

Results The morphology of the type IV DDH true acetabulum was mostly triangular. The intraoperative reaming centre were centered on the upper two thirds of the posterior border of the true acetabulum. The postoperative 3D CC was 80.20% ± 7.63% (64.68–90.24%, 44–48-mm cup size). The patients' mean Harris score improved from 39.7 ± 20.4 preoperatively to 91.5 ± 8.12 at the last follow-up.

Conclusion Our study demonstrated that satisfactory CC and clinical results could be achieved by implanting a standard-sized cup with the reaming centre on the upper two thirds of the posterior border of the true acetabulum.

Keywords Developmental dysplasia of the hip (DDH) · Crowe IV · Total hip arthroplasty

Abbreviations

DDH Developmental dysplasia of the hip
THA Total hip arthroplasty

Introduction

Developmental dysplasia of the hip (DDH) is a common cause of secondary hip arthritis [1, 2]. Due to anatomical variations, the treatment of DDH through total hip arthroplasty (THA) is still a challenging task, especially for patients with Crowe type IV.

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Although the fundamental principle of acetabular cup placement in Crowe IV patients remains consistent, THA for type IV patients still presents certain controversies and challenges in achieving optimal acetabular cup placement [3–5], and it is difficult to implant a cup that is as close to the standard size as possible and still achieve adequate cup coverage (CC) without affecting joint motion. Due to the lack of anterior bone mass, placing the acetabular cup posterosuperior to the acetabulum has become an option worth considering [3, 6]. Nevertheless, merely adjusting the acetabular cup superiorly or posteriorly may decrease the range of motion (ROM) of the affected limb while enhancing bone coverage [3, 5].

In addition, the size of the cup also has a significant impact on the success of reconstruction. During the process of Crowe IV reconstruction, ultrasmall cup sizes are often used to obtain satisfactory bone coverage [6]; most surgeons tend to use small acetabular cups with a diameter less than or equal to 44 mm [7]. However, small acetabular prostheses also have some disadvantages, such as limiting the thickness of the polyethylene liner, thereby shortening the life of the implant [8], limiting the size of the femoral head, thereby jeopardizing the stability of the joint, and limiting the use of a more durable and more stable COC bearing pair with a minimum outer cup size of 44 mm [9, 10].

Our previous research demonstrated that in type IV patients, a standard size cup ($\geq$ 44 mm) could be successfully implanted in a specific posterosuperior area of the true acetabulum, resulting in satisfactory cup coverage [6]. Midterm outcomes were also excellent in those patients.

However, previous studies have only given rough guidelines for acetabular cup placement rather than method to guide intraoperative reaming. The previous placement highlighted the spatial placement of the cup, and we wanted to find new anatomical landmarks, which we called anatomical placement. Moreover, due to the anatomical variation of patients with type IV dysplasia, the lack of reference markers such as the transverse acetabular ligament for cup reaming has not been fundamentally resolved [11, 12]. This is not conducive to guiding the implantation of standard cups during surgery.

In this context, we carried out this research. The main objectives of the study were (1) to find a reliable method to determine the reaming center intraoperatively in THA for DDH type IV patients; (2) to evaluate the feasibility of this method by surgery; (3) to study the impact of this location on the impingement-free range of motion of the hip; and (4) to further study the impact of this method on the patient's mid-term clinical performance.

Materials and methods

Study design and setting

We performed a single-center, retrospective analysis of prospectively collected data. This single-centre retrospective matched study has been approved by the local Ethics Committee (SH9H-2019-TK299-1). This study is conducted and reported in line with the STROCSS criteria [13].

Patients

From January 2017 to December 2019, 86 total hip arthroplasties were performed on 66 patients with high dislocation hip dysplasia in our hospital. According to the Crowe classification [14], all hips were classified as type IV. All patients should use the method we describe below to determine the acetabular reaming centre. Based on that, 66 were eligible; 7.5% (five of 66) of patients were excluded because of incomplete preoperative or postoperative CT. An additional three patients were lost during follow-up because of incomplete datasets or follow-up less than one year, leaving 87.8% (58 of 66) for analysis here. Among them, eight patients had bilateral hip surgeries, all performed on the same day.

There were six men and 52 women. The mean age was 49.71 ± 15.49 years old. The demographic data are shown in Table 1.

This study was approved by the ethics committee of our institution.

Analysis of acetabular structure and determination of the intraoperative acetabular reaming center

We first focused on finding a reliable Acetabular Beginning Reaming Centre for intraoperative cup implantation. By collecting imaging data from our previous study [6], we performed a series of three-dimensional (3D) reconstructions of the postoperative pelvis using Mimics software (version 20.0; Materialize, Leuven, Belgium). The egg-shell cup position was adjusted in the orthographic coronal and transverse images until it was oriented at 45° abduction and

Table 1 Demographic data

Variables	Value
Number of patients	58
Females: males	52:6
Age (years)[a]	49.71 ± 15.49 (19–79)
Height (mm) [a]	157.56 ± 6.62 (145–165)
Weight (kg) [a]	57.33 ± 6.44 (48–65)

[a]Values expressed as means ± SD, with ranges in parentheses

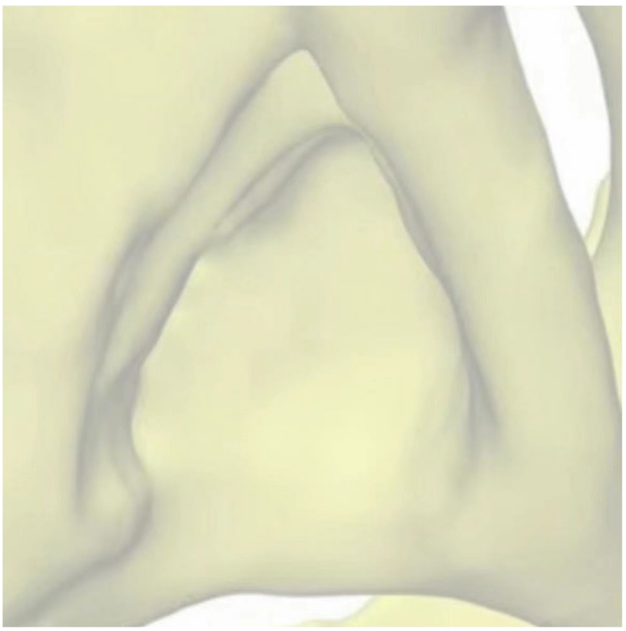

Fig. 1 The acetabular structure of Crowe IV patients is approximately triangular

20° anteversion. It was found that the acetabular structure of Crowe IV patients mainly presented an anatomical feature of approximately triangular shape (Fig. 1).

Next, the point of center of rotation (COR) was projected on the bone surface by Yong Nie's method [15]. Points a and b are located at the two poles of the prosthesis and are connected by arcs ab. Line cd is perpendicular to line ab and originates from the midpoint c of line ab. This results in a line passing through points a, b, and c, which passes through the largest cross section of the acetabular cup. Point d is the junction of the acetabular cup and the bone; this is the point at which the COR is located on the bone surface, which represents the point at which the rasps are aligned (Fig. 2). The outer wall of the acetabular cup is tangent to, but does not penetrate, the inner cortical layer of the pelvis.

Finally, we label the COR projection points on the bone surface with different colors and map the COR on the 2D projection of the patient's preoperative 3D reconstruction. By taking the unique true acetabular anatomy of Crowe IV patients as a reference and matching the points into this triangular acetabulum, we found that most of the projection points on the bone surface of the CORs were located on the upper two third of the posterior border line. We believe this point can be used as a central point for intraoperative reaming (Fig. 3A). And, in a new cohort of follow-up patients undergoing hip reconstruction, this location was used as the starting point for intraoperative reaming rather than the COR after reconstruction. In subsequent surgical procedures, after exposing the patient's deformed acetabular structure, we chose this starting point for reaming.

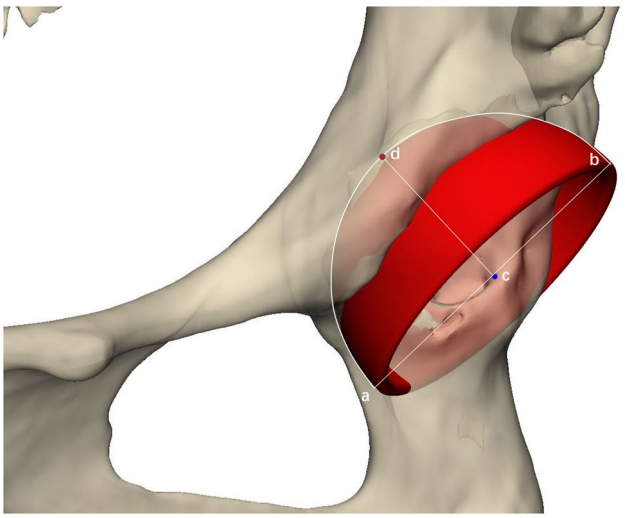

Fig. 2 Reconstruction of the pelvis from postoperative imaging data

Operation

All surgical operations were performed by two senior surgeons (HWL, ZAZ) through a posterolateral approach. The surgical method was consistent and mature as previously described [16]. To clearly see the true acetabulum and fully grasp the anatomical landmarks in the acetabulum, the osteophytes around the acetabulum and the hypertrophic soft tissues that obstructed the view were removed.

The starting point for reaming was defined as the upper two thirds of the posterior border of the true acetabulum. During the reaming process, the direction of the ream was always toward the posterior and inferior, thus ensuring the integrity of the anterior wall of the acetabulum, because most of the bone mass is located in the posterior and inferior [3, 17, 18]. Acetabular component fixations were uncemented in all hips at 20–30° anteversion. Stop reaming when the cortex of the acetabular fossa can be seen. When good stability was obtained, partial noncoverage of the upper outer edge was considered acceptable [19].

Patients were allowed to bear partial weight after surgery, but full weight loading was not allowed until six weeks after surgery.

Cup three-dimensional (3D) coverage calculation (CC)

We collected the patient's CT data within 3 days after the operation and imported the DICOM format data into Mimics to perform the 3D reconstruction of the pelvis, including the complete prosthesis according to the preoperative 3D reconstruction method.

To eliminate the influence of prosthesis artifacts on the CC measurement, we reconstructed a smooth cup with the

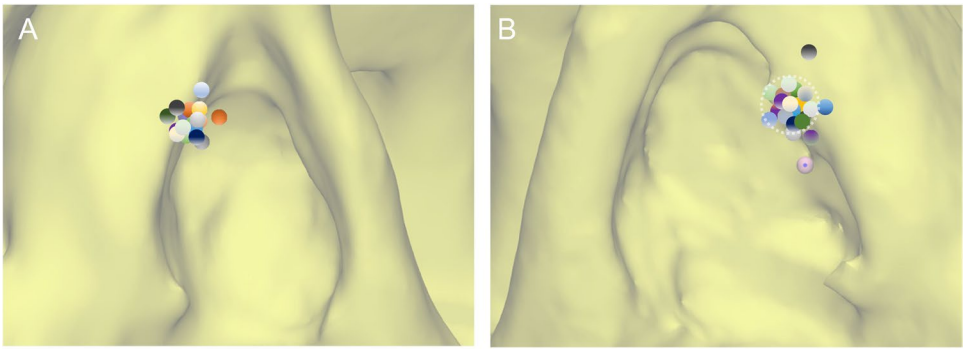

Fig. 3 The location of the postoperative centre of cup relative to the true acetabular of patients with Crowe type IV. Different colors refer to different acetabulum. **A** Reaming centre determined by retrospectively collected imaging data. **B** Projection of the centre of rotation obtained from postoperative CT data of the patients included in this study

same size and direction according to the 1:1 principle. The original prosthesis was replaced with a smooth cup for bone coverage measurement (Fig. 4).

The Mimics Boolean function was used to determine the percentage of cups that were not covered with bone, that is, the percentage of exposed surface area (SU). The total surface area (St) was available, and the CC was calculated as [20].

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

Measurement of impingement-free range of motion (ROM)

Simulating the range of motion (ROM) through computer 3D reconstruction techniques proves to be an effective method for accurately reflecting hip mobility [21–24]. We performed ROM measurements by using Solidworks™ (version 2021; Dassault Systemes S.A., MA, USA). This study used the transverse plane described by Jóźwiak et al. [25] to establish a reference plane starting from the base of the sacrum. Measurements are individually designed for each patient. First, we determined the geometric centre of the base of the sacrum and the centre of the junction of the pubic tubercle, aligned the sagittal plane perpendicular to the transverse plane and coincided it with the midpoint of the line connecting the two centres. In addition, we ensured that the coronal plane was perpendicular to the transverse and sagittal planes and coincided with the geometric centre of the sacral base. Next, the neutral position and joint range of motion of the lower limbs were specified by establishing a coordinate system in three-dimensional space. The x-axis was formed by the intersection of the coronal and transverse planes; the y-axis was orthogonal to the x-axis and lay in the coronal plane; the z-axis was perpendicular to the x- and y-axes and was anteriorly aligned (Fig. 4A) [26, 27].

The pelvis was mobilized according to the method we introduced before [28], the femoral portion was rotated around the X, Y, and Z axes until impact occurred, and the angle of rotation, including the angles of flexion, extension, adduction, abduction, internal rotation, and external rotation, was recorded.

Clinical assessment

Postsurgical clinical evaluation of each patient was performed at regular intervals at one, three and six months and then annually. We clinically evaluated each patient with the Harris Hip Score [19], prosthesis revision rates, patient

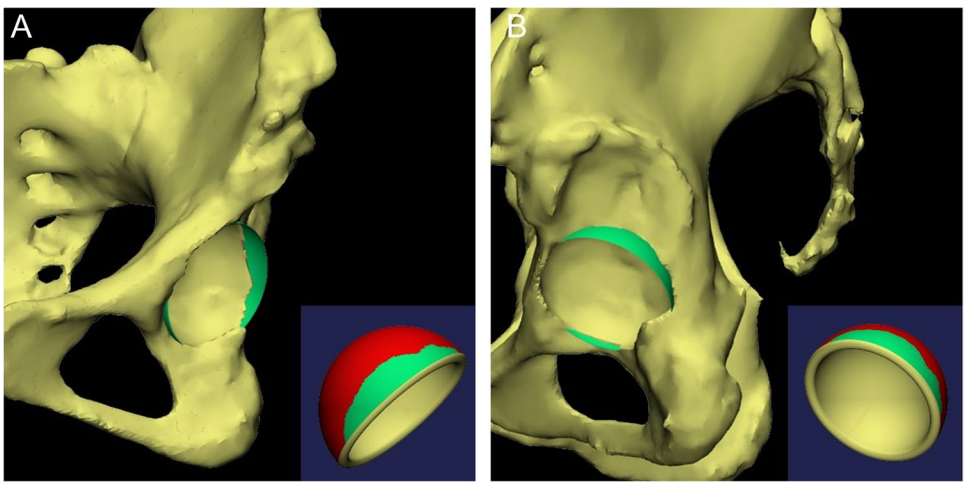

Fig. 4 Measurement of acetabular cup coverage. **A** Coronal view: segmented according to the boundary between the covered part (red area) and the uncovered part (green area) of the cup model. **B** Sagittal view

reported postoperative limp, and surgery-related complications including infections, dislocations, fractures, and vascular/nerve damage.

Statistical analysis

All statistical analyses were performed using SPSS software for Windows (version 24; SPSS, Chicago, IL). Continuous variables such as demographics, radiographic measurements, and clinical scores were expressed as mean and standard deviation.

Results

Bone coverage of the acetabular cup

Bone coverage at each hip is shown in Table 2. The postoperative simulated maximum 3D CC was 90.24%. The simulated mean 3D CC was 80.20 ± 7.63 (64.68–90.24%) with acetabular cups 44 to 48 mm in size (44 mm for 15, 46 mm for 9, 48 mm for 10). Except for one patient whose bone coverage was 64.68% (cup size: 44 mm), the cup bone coverage of all the other patients exceeded 70%.

The centre of rotation after surgery

Projection of the COR on the bone surface of the patient's affected acetabulum was centered around the reaming centre we designed which is the upper two thirds of the posterior border of the true acetabulum (Fig. 3B). This is consistent with the location of the acetabular reaming centre in our preoperative planning.

Impingement-free mobility simulation

According to previous research, the required range of motion (ROM) was defined as flexion ≥ 110°, internal rotation (IR) at 90° flexion ≥ 30°, extension ≥ 30°, and external rotation ≥ 30° [5]. As shown in Fig. 5 and Table 3, among the Crowe IV DDH patients who underwent THA in our institution, the hip flexion was 121.36° ± 9.28°, the extension was 37.03° ± 13.25°, and the external rotation was 40.56° ± 16.71°. The above data all meet the criteria for a good range of joint motion after THA. It is worth noting that among the surgical patients, there was a patient with a combined anteversion angle of 65°, resulting in a simulated postoperative joint extension range of 20.43°. The patient's joint was stable during up to five years of postoperative follow-up, with no re-dislocation or readmission for revision surgery, so we consider the clinical outcome of this case to be acceptable.

These data suggest that implantation of a standard acetabular cup in the upper two thirds of the posterior border of the true acetabulum can ensure adequate CC while maximizing the preservation of joint mobility.

Table 2 Three-dimensional (3D) measurements of cup coverage

Variables	3D measurement
Number of patients (hips)	58 (78)
Coverage (%)	80.20 ± 7.63
Minimum (%)	64.68
Maximum (%)	90.24

Clinical outcomes

The clinical results are shown in Table 4. One case of joint dislocation occurred during follow-up. The cause was a rupture of the high side of the polyethylene liner due to the excessive abduction angle (70°), which was resolved by subsequent revisions. It is worth noting that this angle is the abduction angle relative to the horizontal ground, not the commonly used abduction angle relative to the pelvis. This excessive abduction angle is due to the recovery of the tilted pelvis after the operation. One patient suffered intraoperative femoral nerve injury. The clinical symptoms of nerve injury improved six months after the operation, and the symptoms disappeared at the one year follow-up. The nerve damage here was considered to be caused by excessive stretching caused by inadvertent operation during the operation. No significant vascular damage was found during surgery. Four patients reported mild limp at subsequent follow-up. In addition, no other complications were found during follow-up. A significant improvement in the HHS after the surgery was observed as well. The patients' mean Harris score improved from 39.7 ± 20.4 preoperatively to 91.5 ± 8.12 postoperatively.

Discussion

While the surgical principles for total hip arthroplasty (THA) in patients with DDH Crowe type IV are well-established, there remain unresolved challenges in the specific procedural execution. For Crowe IV DDH patients, how to determine the acetabular reaming center intraoperatively is still a challenging task. Particularly when aiming to implant a standard size acetabular cup instead of smaller cups, the primary challenge arises from the absence of suitable anatomical landmarks for reference [6, 18, 29, 30]. Therefore, this study aimed to utilize 3D reconstruction and simulation techniques to devise a method capable of guiding the reaming process in patients with Crowe type IV DDH, leveraging the distinctive anatomy of the acetabulum in these individuals.

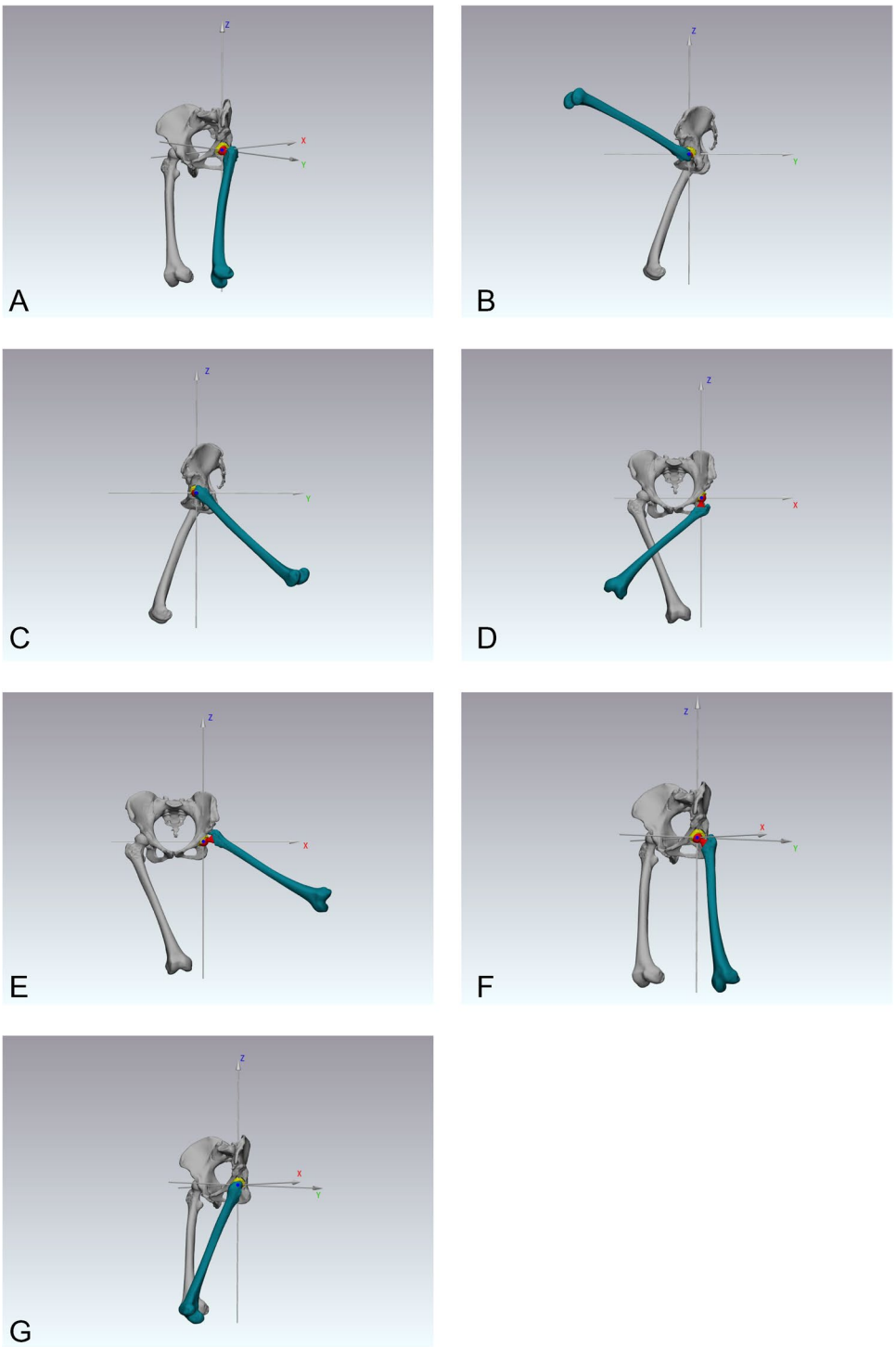

Fig. 5 **A** Neutral position. **B** Hip flexion. **C** Hip extension. **D** Hip adduction. **E** Hip abduction. **F** Hip external rotation. **G** Hip internal rotation

Due to the existence of anatomical defects, including a flat acetabulum and insufficient bone mass [31, 32]. It is often difficult to decide intraoperatively where to start reaming, and to implant the acetabular component into the acetabulum while obtain satisfactory CC, especially in the true acetabulum. A CC of at least 70% has become the accepted value, which may ensure cup initial stability and prevent early loosening [20, 33].

Various acetabular reconstruction techniques have been recommended to increase the CC, including the use of small acetabular cups [3, 5, 20]. However, a small acetabular cup will inevitably limit the size of the femoral head

Table 3 Measurement of joint range of motion obtained by computer simulation

Variables	Mean value	Standard deviation	Minimum	Maximum
Flexion (°)	121.36	9.28	112.22	142.51
Extension (°)	37.03	13.25	20.43	59.84
Adduction (°)	37.01	10.77	21.25	58.31
Abduction (°)	71.51	21.39	34.76	110.38
External rotation (°)	40.56	16.71	17.13	76.70
Internal rotation (°)	69.71	26.73	18.22	110.33

IR internal rotation, *ER* external rotation

Table 4 Clinical results after total hip arthroplasty

Parameter	Outcome
Operative time, min (SD)	133.4 (41.7)
Perioperative bleeding, mL (SD)	273.0 (34.3)
Patients' satisfaction	
Excellent	55
Good	1
Moderate	2
Unsatisfactory	0
Prosthesis revision (%)	1 (1.7%)
Surgery-related complications	
Infection (%)	0
Dislocation (%)	1 (1.7%)
Intraoperative fracture (%)	0
Blood vessel/nerve damage (%)	1 (1.7%)
Limp	4/58
Harris hip score	
Before operation (SD)	39.7 (20.4)
After operation (SD)	91.5 (8.12)

SD standard deviation

prosthesis while obtaining sufficient CC, thus impairing the stability of the hip joint [8]. In addition, small cups restrict the use of more durable and stable COC bearing pairs which requires a minimum outer cup size of 44 mm [9, 10, 34, 35]. Therefore, the small cup is an important factor leading to the redislocation of the hip joint during the follow-up. To determine where a standard size (≥ 44 mm) acetabular cup can be implanted, our previous research used 3D reconstruction technology to simulate implantation, and we found that reconstruction of the cup in the real acetabulum without proper placement inevitably resulted in a CC of less than 70%. Studies have also found, when the centre of the cup moves to the posterosuperior side of the acetabulum, where the bone mass is abundant, a significant increase in the CC can be observed [6].

Nevertheless, only determining the approximate area of the cup without giving the precise point for reference is not enough to guide the reaming during the operation. That is to highlight the role of anatomical landmarks in acetabular reaming rather than just relying on sensation. However, due to the severe deformation of the acetabular structure in highly dislocated patients, the true acetabular structure of type IV patients is completely different from that of Crowe type I–III patients [3, 15, 18, 20, 29, 36, 37]. Structures that are often used as important anatomical reference landmarks in THA surgery, such as the severe absence or deformation of the transverse acetabular ligament and the deformation of the acetabular horseshoe fossa, all interfere with the operation [38, 39]. Choosing where to ream and to implant the cup in the true acetabulum during surgery can be challenging, even when it is clear the cup's COR should be positioned posterosuperior to the acetabulum for maximum bone coverage.

Using imaging data from our previous study [6] and with the aid of computational techniques, we found that the acetabular structure of type IV DDH patients is approximately triangular. And we concluded that after reconstruction with standard-sized cups, the projection point of the postoperative COR on the bone surface of the preoperative acetabulum is centered on the upper two thirds of the posterior border of the triangular acetabulum. Subsequently, we included a new cohort of patients and opted to ream in the upper two thirds of the posterior border of the true acetabulum. Again, it was confirmed that starting acetabular reaming at this point is beneficial for consistent cup implantation (Fig. 3B). Furthermore, the CC of the cups implanted there all reached or exceeded 70% with cup size of 44–48 mm, except one hip. Relevant studies have shown that a CC above this value helps to maintain good mid-term outcomes after THA [20, 40, 41]. Most notably, the small-sized cups typically used in patients with severe acetabular dysplasia can also be replaced with standard-sized cups ≥ 44 mm [42, 43].

On the premise of ensuring adequate bone coverage, it is also important to reconstruct the ROM of the hip joint. Yuta Sakemi et al. [3] conducted a study on Crowe type II/III patients and showed that posterosuperior cup placement gained more bone coverage but decreased the range of hip flexion and internal rotation. Keisuke Komiyama et al. [5] reported that in the vertical position, a higher hip centre gained more bone coverage but decreased the range of hip flexion and internal rotation. These previous studies suggested that under the premise of obtaining sufficient CC, we should also consider the impact of the cup on the ROM of the joint. Therefore, after obtaining a satisfactory cup implantation through postoperative CT films and computer simulation, we further performed impingement-free simulations to determine the influence of the cup on hip joint. In this study, the joint impingement test of the joints in all directions was satisfactory, except for one

patient whose extension was only 20° due to the relatively high combined anteversion.

As for the clinical results, the reaming centres we reported can guarantee the successful completion of the operation, and all of them successfully implanted standard-sized cups(44–48 mm) in the predetermined positions. There was no surgical failure caused by the destruction of the acetabular due to reaming during the operation, and there was no need for other methods such as internal fixation to assist in reconstruction, nor was there any reconstruction that required an ultra-small acetabular cup to complete. In addition, there was no mechanical loosening due to insufficient initial stability, indicating that the surgical approach achieved adequate coverage and initial stability. For patients and surgeons, limp is one of the most frustrating persistent symptoms after hip replacement for type IV DDH. There are many reasons for limp [44, 45]. Crowe IV patients often have this complication after THA due the centre of rotation was moved up too much [5, 17]. However, a lower incidence of limp was observed during the medium-term follow-up in our research, suggesting the reliability of this method in satisfactory walking function postoperatively. We also aim to underscore the critical importance of meticulous reduction intraoperatively to prevent any unnecessary nerve traction injuries. Finally, only one patient developed dislocation due to excessive abduction angle which leads to the high side rupture of polyethylene lining during postoperative follow-up, indicating that stable joints can be obtained by surgery.

There were several limitations of our study. Firstly, this study did not incorporate the influence of periarticular soft tissues, such as ligaments and muscles, on joint mobility, which are vital factors in actual joint movement. Given the limitations of current computer software analysis capabilities, this deficiency is inevitable. Due to the existence of soft tissue around the joint and the limitation of the prosthesis, there is a difference between computer-simulated joint mobility and actual joint mobility. However, our clinical follow-up results also confirmed that the ROM of the joints can meet the daily needs of young patients with low dislocation rate. Second, our conclusion is based on a relatively small sample size. Future studies should further strengthen our conclusions with the scope of a multicenter large group study. Third, our follow-up is a mid-term follow-up, which can effectively observe the reaming center on the success rate of cup implantation and initial stability, but the impact of this position on long-term survival such as prosthesis wear still needs further observation.

Conclusion

Our research results showed that adequate bone coverage and satisfactory clinical outcomes could be obtained by implanting a standard-size cup with the intraoperative reaming centre at the upper two thirds of the posterior border of the true acetabulum. We believe that this study will serve as a valuable reference for other orthopaedic surgeons seeking to locate the reaming centre in hip reconstruction procedures for treating Crowe type IV patients.

Author contribution Chen Zhao: data collection, investigation, software, writing original draft. Keyu Kong: methodology, supervision, formal analysis. Xiaohui Ding: formal analysis, supervision. Zhenan Zhu: conceptualization, supervision, formal analysis. Huiwu Li: supervision, validation. Jingwei Zhang: funding acquisition, conceptualization, methodology, project administration, writing—review and editing.

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Data availability All data supporting the findings of this study are available in the article and Supplementary Information files. Any additional requests for information can be directed to and fulfilled by the corresponding authors. The source data are provided in this report.

Declarations

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Patients signed informed consent regarding publishing their data and photographs.

Conflict of interest The authors declare no competing interests.

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A statement of the location where the work was performed The main work of this study was done at the Ninth People's Hospital Affiliated to Shanghai Jiaotong University School of Medicine (Shanghai, China).