CLINICAL ARTICLE

Three-dimensional Computerized Preoperative Planning of Total Hip Arthroplasty with High-Riding Dislocation Developmental Dysplasia of the Hip

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Objective: To assess whether computed tomography (CT)-based 3-dimensional (3D) computerized pre-operative planning is accurate and reliable in patients with high-riding dislocation developmental dysplasia of the hip (DDH) undergoing total hip arthroplasty (THA).

Methods: Between September 2009 and February 2011, a prospective study with an inbuilt means of comparing predictive techniques in 20 patients (20 hips) with high-riding dislocation DDH was undertaken. All patients had pre- and post-operative CT scans, data from which were transferred digitally to Mimics software. 3D pre-operative planning to predict the acetabular component size, hip rotation center position and acetabular component coverage was performed using Mimics software. The results and post-operative course were compared with those of the traditional acetate templating technique.

Results: Using 3D computerized planning, 14/20 components (70%) were predicted exactly and 6/20 (30%) within one size, whereas with the conventional acetate templating technique, 5/20 components (25%) were predicted exactly, 9/20 (45%) within one size and 6/20 (30%) within two or more sizes. There was a strong correlation between the 3D computerized planned acetabular component size, hip rotation center distance, acetabular component host coverage and that found postoperatively. Five patients were considered to need structural bone graft on the basis of 3D computerized planning; this was highly coincident with the intraoperative findings in all five cases.

Conclusion: CT-based 3D computerized pre-operative planning using Mimics software is an accurate and reliable technique for patients with high-riding dislocation DDH undergoing THA.

Key words: Developmental dysplasia of the hip; Hip arthroplasty; Mimics software

Introduction

The term developmental dysplasia of the hip (DDH) refers to a broad spectrum of abnormalities involving the growing acetabulum and adjacent femur. Patients with DDH have distorted acetabular anatomy that makes total hip arthroplasty (THA) technically demanding, especially in those with the

high-riding dislocation type¹⁻³. The common characteristics of DDH are acetabulum anteversion increased, hypoplastic triangular morphological abnormality, anterolaterally and superiorly acetabular bone deficiencies, small femoral head, short femoral neck with markedly anteverted, and femoral intramedullary canal decreased. Furthermore, in a high dislocation DDH

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Disclosure: No authors have financial or personal relationships with other people or organizations that could inappropriately influence this work. This research was funded by the China Health Ministry Program (201302007).

Received 5 October 2013; accepted 28 February 2014

patient, the femoral head migrates superiorly and posteriorly in relation to the true acetabulum, which causes abnormal soft tissue and the sciatic nerve around the hip. For these abnormalities, more technical difficulties encountered during a THA for DDH patient, such as how to reconstruct acetabulum, how to choose hip rotation center, whether or not to perform bone graft and subtrochanteric osteotomy. As previous studies have reported, comprehensive preoperative planning is essential for these patients to minimize the duration of the surgical procedure and the incidence of complications⁴⁻⁹.

Traditionally, preoperative planning is performed using acetate templates superimposed on printed radiographic films; this technique has gradually been replaced by use of digital images^{4,10-12}. However, these two-dimensional images lack three-dimensional (3D) information, making accurate quantification for prosthesis selection and location difficult, especially for the acetabular component^{6,13,14}. To the best of our knowledge, few previous studies have reported the accuracy and reliability of 3D computerized preoperative planning of acetabular prostheses in THA in patients with high-riding dislocation DDH.

In the present study, we ascertained whether: (i) 3D computerized planning utilizing Windows-based Mimics software is accurate and reliable at predicting acetabular component size in patients with high-riding dislocation DDH, by comparing with the predicted component size with the size of that placed surgically; (ii) 3D planning is useful for determining the hip rotation center and acetabular component cover-

age, which can guide bone grafting intraoperatively; and (iii) 3D planning can provide more accurate and reliable information than the traditional acetate templating technique.

Materials and Methods

Between September 2009 and February 2011, a prospective study with an inbuilt means of comparing predictive techniques in 20 patients (20 hips) with high-riding dislocation DDH was undertaken. The study subjects comprised 16 women and 4 men, with a mean age of 45 years (26–60 years) and a mean body mass index of 24 kg/m² (17–26 kg/m²). The operated side was the right in 7 patients and left in 13. According to the classification of Crowe *et al.* (class I, less than 50% subluxation; class II, 50% to 75% subluxation; class III, 75% to 100% subluxation; class IV, more than 100% subluxation), all the included high-riding dislocation DDH patients were class IV. All THAs were performed by one senior surgeon (SB) via a posterolateral approach, using cementless Pinnacle acetabular implant (DePuy, Warsaw, IN, USA).

In all patients, 3D preoperative planning based on computed tomography (CT) scan data was performed using Mimics software. All patients had pre and postoperative CT scans. One senior radiological consultant (ZX) and two orthopedic surgeons (ZY, LOJ) made all measurements.

This study was approved by the local institutional review board. All investigations were conducted in conformity with ethical principles of research. Informed consents for this study were obtained from all patients.

Fig. 1 Four images are simultaneously displayed on one field. (a) Coronal image. (b) Transverse image. (c) Sagittal image. (d) Reconstructed 3D pelvic image. The cross-lines are used for simultaneous accurate positioning in different views.

Fig. 2 An image of the acetabular component models conserved in Mimics software. These models had 12 different diameters that increased stepwise by 2 mm, the smallest being 38 mm and the largest 60 mm. The acetabular cup model thickness was 4 mm.

CT Scan Protocol and Pelvic Reconstruction

3D bone images of the pelvis were reconstructed and analyzed using Mimics software version 10.01. Digital Imaging and Communications in Medicine data from CT images were imported into Mimics, and the pelvis selected as the reconstructive target; the regional shade growing and editing technique was used. After completion of reconstruction, the 3D pelvic, cross-sectional transverse, cross-sectional sagittal and cross-sectional coronal images were simultaneously displayed on one field of view (Fig. 1). The resultant pelvic image could be rotated to any angle in 3D space according to the researcher's requirements.

Acetabular Prosthesis Simulated Implantation

Prior to simulated implantation, a computer-aided design format (CAD, Unigraphics NX, EDS) was used to design a spectrum of hemispherical models according to the design features of the Pinnacle component of prosthesis. These acetabular prosthetic models had 12 different diameters that increased by 2 mm steps, the smallest being 38 mm and the largest 60 mm. The thickness of the acetabular cup was 4 mm. These 3D models were imported and conserved in Mimics software (Fig. 2).

After creating the 3D image of pelvis and the acetabular prosthetic model, preoperative simulated prosthesis implantation was performed. The acetabular model was adjusted in orthographic coronal and sagittal images until it was positioned at the level of the true acetabulum, oriented in 45° abduction and 15° anteversion. The inferior rim of the acetabular model was placed at the level of the teardrop

bottom and so-called rim press-fit in acetabulum achieved. In the transverse image, the acetabular model was confined by both anterior and posterior columns. The whole implantation process was similar to actual surgical procedures, 3D, coronal, sagittal and transverse images being clearly shown in Mimics interface simultaneously (Fig. 3). After the model position had been determined, different sizes of model from the smallest to the largest were tested; these presented a 3D surface in space or an outline in transverse images. Modular implants of dimensions greater than acetabular size that penetrated into the inner cortex were excluded for further implantation. The optimal implant had a good match with the true acetabulum, the largest surface contact area with anterior and posterior columns and best position in the true acetabulum.

Hip Rotation Center Measurement

After the size and position of the acetabular model had been determined, the central point of the implant model was defined as the hip rotation center. To calculate the position of the hip rotation center, a coronal view through the modular central point was created. The point of intersection between a horizontal line through the top of the symphysis pubis and its vertical line was defined as the reference point in the coronal plane. Starting from this reference point as the center of an X–Y coordinate system, the position of the hip rotation center was identified and represented as vertical and horizontal distances. Using the same method, the position of the hip rotation center as identified preoperatively was compared with the actual position in post-operative CT scans (Fig. 4).

Fig. 3 The acetabular component model was implanted in the true acetabulum in Mimics. Researchers could clearly determine the exact position of the model with the help of Mimics, which makes simultaneous 3D, coronal, sagittal and transverse views possible. Different sizes of model were tested from the smallest to the largest, which presented a 3D surface or line in cross-section areas in Mimics. The optimal implant has a good match with the true acetabulum, the largest surface contact area with the anterior and posterior columns and the best position in the acetabulum.

Acetabular Component Coverage and Bone Graft Measurement

To calculate the acetabular component coverage, after the size and position of the acetabular model had been determined, a

coronal view through the rotation center was created. The method of Silber and Engh was used to measure component coverage, meaning that the component host coverage ratio was calculated as the angle for host coverage divided by 180

Fig. 4 The central point of the implant model was defined as the hip rotation center and identified in a coronal view by measuring vertical and horizontal distances in an X-Y coordinate system starting from the reference point. The positions according to (a) pre-operative planning and (b) post-operative CT scans were compared in order to determine the accuracy of preoperative planning.

(hemispherical angle of component) and multiplied by 100%¹⁵. Mulroy and Harris have recommended that structural bone graft should be used if >30% of the cup is not covered by host bone¹⁶. Hence, if 3D computerized preoperative planning showed a component host coverage ratio <70%, it was anticipated that structural bone graft would be needed.

Implant Size Prediction with Acetate Templating Technique

Standardized radiographs including an anteroposterior view of pelvis and lateral view of the affected hip were taken preoperatively using a digital radiography technique. The hips were internally rotated 10° to overcome the natural anteversion of the femoral neck and all radiographs were obtained with a standardized 100 cm distance from the tube to the X-ray plate, which results in an average 20% magnification as previously reported¹⁷. The 20% magnified acetate templates were superimposed on printed radiographic films to select the most suitable implant size. The radiographs were independently reviewed and templated manually by two senior orthopedic surgeons (YJ, ZZK). Neither of these reviewers knew the actual prosthesis size implanted at surgery.

Statistical Analysis

The distribution of variables was tested for normality using the Ryan–Joiner and Shapiro–Wilk tests. For normally distributed variables, the χ^2 test was performed to determine the differences between 3D computerized planning and acetate templating technique in coincidence rates of component size prediction. The paired Student's *t*-test was used to compare the predicted and postoperative abduction angles of the acetabular component and location of the hip rotation center. For variables lacking a normal distribution or normally distributed variables with unequal variances, the Mann–Whitney *U* test was applied. All statistical analyses were performed using SPSS version 13.0 (SPSS, Chicago, IL, USA) and a *P* value <0.05 was considered to be statistically significant.

To assess intra-observer reliability of the predicted implant size, CT-based 3D imaging and Mimics software technique were performed by one investigator (KPD), who repeated the test one month later. To assess inter-observer reliability, two investigators (ZY, LOJ) performed pre-operative planning independently. Intra-observer and inter-observer effects were calculated using an intraclass correlation coefficient (ICC)¹⁸.

Results

Planned and Actual Acetabular Component Size

The mean predicted acetabular component size was 45 mm (42–48 mm), 1 mm smaller than the mean implanted size of 46 mm (42–50 mm). Given that the acetabular component size increased by 2 mm steps, the difference between mean implanted and mean predicted acetabular component was less than one size. There was a high correlation between the planned acetabular prosthesis size and that determined intra-operatively (0.92, *P* < 0.001).

Planned and Actual Acetabular Abduction Angle

The postoperative acetabular abduction angle was $44.98^\circ \pm 10.83^\circ$ (32.00°–59.32°) representing an increase of $9.71^\circ \pm 4.25^\circ$ (4.25°–14.20°) compared with the planned value of $41.10^\circ \pm 4.87^\circ$ (32.61°–45.27°, *P* = 0.42). There was no substantial correlation between the planned acetabular abduction angle and that measured post-operatively (0.22, *P* = 0.67).

Planned and Actual Hip Rotation Center

The postoperative horizontal distance of the hip rotation center was 79.85 ± 8.61 mm (65.23–88.25 mm) representing an increase of 3.26 ± 1.35 mm (1.35–5.35 mm) compared with the planned value of 77.51 ± 7.78 mm (68–86.51 mm, *P* = 0.109). There was a strong correlation between the planned horizontal distance and the actual horizontal distance post-operatively (0.94, *P* = 0.005). The postoperative vertical distance of the hip rotation center was 45.3 ± 4.6 mm (41.09–53.36 mm) representing an increase of 4.51 ± 2.58 mm (0.86–7.32 mm) compared with the planned value of 42.79 ± 8.22 mm (35.43–58.51 mm, *P* = 0.262). There was a strong correlation between the planned vertical distance and that found postoperatively (0.86, *P* = 0.027).

Planned and Actual Acetabular Component Coverage

The post-operative acetabular component host coverage ratio was $78.98\% \pm 10.24\%$ (65.11%–90.94%) representing an increase of $2.32\% \pm 1.37\%$ (0.44%–5.97%) compared with the planned value of $77.73\% \pm 10.51\%$ (60.45%–92.12%, *P* = 0.09). There was a strong correlation between the planned acetabular component host coverage and that found postoperatively (0.97, *P* < 0.001). Five patients were considered to need structural bone graft according to 3D planning (their host coverage ratios being 69.40%, 65.41%, 60.45%, 67.14% and 68.41%); these predictions were strongly coincident with the postoperative results (postoperative host coverage ratios were 64.23%, 68.13%, 66.41%, 65.11% and 66.17%) (Fig. 5).

Comparison of 3D Planning and Conventional Acetate Templating Technique

The predictability of acetabular component size is shown in Table 1. For 3D planning, 70% of acetabular components (14/20) were predicted exactly (corresponded to the size placed intraoperatively). Thirty percent (6/20) were accurate within one component size. No components were accurate within two or more component sizes. For the conventional acetate templating technique, 25% of acetabular components (5/20) were predicted exactly (*P* = 0.047 compared with prediction by 3D planning), 45% (9/20) were accurate within one component size (*P* = 0.096 compared with prediction by 3D planning) and 30% (6/20) were accurate within two or more component sizes.

Reliability of the Predicted Acetabular Component Size

With the 3D planning method, the ICC for intra-observer reliability for acetabular component size prediction was 0.81 and for inter-observer reliability 0.87, which indicates almost perfect reliability for component size predictability.

Fig. 5 CT based 3D computerized pre-operative planning for a 38-year-old woman with congenital left high-riding dislocation of the hip. (a) Her pelvis was reconstructed by Mimics software and an acetabular model positioned at the level of the true acetabulum. (b) A coronal view through the modular central point was created and the component host coverage ratio measured (the host coverage ratio was $\alpha/180 \times 100\%$). This patient's component host coverage ratio was 69.4%, which is considered to need structural bone graft. (c, d) Immediate postoperative pelvic anteroposterior radiograph and CT scan, demonstrating the component supported by structural bone graft (postoperative host coverage ratio was 64.23%). The results between 3D computerized pre-operative planning and post-operation were strongly coincident.

Discussion

Several previous studies have reported the predictability of acetabular component prostheses in THA. Davila *et al.* assessed the accuracy of computer-assisted templating in THA patients and reported that 86% of acetabular components were accurate within one size⁵. Iorio *et al.*¹² and Suh *et al.*¹⁹ reported that preoperative planned sizes of acetabular cups by templating were highly coincident with the sizes used intraoperatively. However, some studies have reported poor accuracy of predicted acetabular prosthesis size in DDH patients. Zhao *et al.* assessed patients with Crowe type II–III dysplastic hips

and found that acetabular prosthesis size prediction accuracy (within one size) was only 48.8%⁶. Unnanuntana *et al.* reported that acetabular prostheses were exactly predicted in 46 of 109 THA patients (42.2%)¹³. They concluded that the main factor explaining the poor accuracy was that 62.4% of included patients had dysplastic hips, which indicates that the templating technique has limited ability to predict acetabular prostheses for DDH patients.

Nowadays, more and more studies have reported the usefulness of 3D images in THA simulated implantation. Ito *et al.* investigated the distribution and degree of acetabular dysplasia and concluded that 3D CT can provide valuable information concerning type of deficiency and degree of acetabular dysplasia⁷. Sariai *et al.* assessed 223 patients undergoing THA in whom the 3D technique was used preoperatively. The components implanted were the same as those planned in 86% of the hips for acetabular implant, 94% for the stem and 93% for the neck-shaft angle²⁰. Davila *et al.* found that the 3D technique predicted acetabular component size well, 86% being within one component size of that used, and 94% within two sizes⁵. Using a 3D model, Abolghasemian *et al.* studied the direction and biomechanical consequences of hip center of rotation migration in Crowe type III and IV hips after THA²¹. In our study, the simulated implantation technique was

TABLE 1 Predictability of acetabular component size in 20 cases (cases [%])

	Exact*	Within one size†	Within two or more sizes
3D computerized planning	14 (70)	6 (30)	—
Acetate templating technique	5 (25)	9 (45)	6 (30)

Compared with the acetabular size predictability (χ^2 test), *, $P = 0.047$; †, $P = 0.096$.

based on 3D imaging and Mimics software using different sizes of acetabular component model for implantation. This technique predicted acetabular component size exactly in 70% patients with high-riding dislocation DDH and 100% within one size: this is obviously more accurate than the acetate templating technique and results of previous studies^{6,13}.

One major technical difficulty encountered during THA for DDH patients involves acetabular reconstruction in patients with high-riding dislocation; the incidence of complications and poor results appears to correlate with abduction angle and position of the acetabular prosthesis^{22–26}. In our study, the mean preoperative acetabular abduction angle was 41.1°, which represents a mean of 9.71° less than the actual value. The center of rotation of the hips was restored with a mean accuracy of 4.51 mm between planned and actual positions of the center vertically and 3.26 mm horizontally: these differences are not statistically significant and are more accurate than those previously reported for other studies²⁷. In addition, for mechanical reasons, orthopedic surgeons favor placing the acetabular component at the level of the true acetabulum^{28–30}. However, it is difficult to identify the true acetabulum in both preoperative templating and surgery. In this regard, Stans *et al.* reported that acetabular components were placed outside the true acetabulum in 25.7% of Crowe type III dysplasia hips³⁰ and Pagnano *et al.* reported 12% in Crowe type II²⁸. In our study, the 3D bone images of pelvis and acetabulum we reconstructed provided a high resolution 3D visualization of the true acetabulum. These 3D acetabular

images could be rotated through 360° in space and cross-sectional transverse, cross-sectional sagittal, cross-sectional coronal and 3D images were simultaneously displayed on one field of view. With this technique, surgeons can identify morphology and bone markers for the true acetabulum and determine the relationship between the true and false acetabulum prior to surgery.

Our study has some limitations. Because of the small patient sample size, there is potential selection bias. Although we compared 3D computerized pre-operative planning and conventional acetate templating technique, we used no other common disease as a control; thus, the proof strength of this study was weak. Furthermore, although this is a prospective study with an inbuilt comparison of predictive techniques, a non-randomized clinical trial study design has inherent selection bias: larger randomized studies are required for more definitive results.

In conclusion, there are multiple options for preoperative planning in THA with regard to DDH. However, the present results show that the 3D technique allows more accurate preoperative planning than the acetate templating technique, especially when deformed anatomies are involved. In addition, the reliability of 3D planning was comparable to that of the template procedure, independent of surgeons and their experience. Therefore, 3D computerized preoperative planning is an accurate and reliable technique for patients with high-riding dislocation DDH undergoing THA.

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