INSTRUCTIONAL COURSE

Preoperative Planning for Total Hip Arthroplasty for Neglected Developmental Dysplasia of the Hip

Xiao-tong Shi[1], Chao-feng Li[1], Cheng-ming Cheng[1], Chun-yang Feng[2], Shu-xuan Li[1], Jian-guo Liu[1]

[1]*Department of Orthopaedics, Jilin University First Hospital and* [2]*Department of Gynecology, Jilin University Second Hospital, Changchun, China*

Developmental dysplasia of the hip (DDH) is accompanied by morphological alterations on both the acetabular and the femoral side. Total hip arthroplasty (THA) provides effective treatment in cases of neglected DDH but requires elaborate preoperative planning. To determine the morphological changes resulting from the dysplasia, the anatomic acetabular position, the height of the femur head dislocation, the height of the femur head dislocation, and the combined anteversion must all be established. In addition, a vital and complicated process of strategizing leg length balance must be conducted in cases of severe DDH. Each type of leg length discrepancy (LLD), including bony and functional and anatomical LLD, should be evaluated in the context of the presence or absence of a fixed pelvic tilt. Moreover, with severe unilateral dislocated hips, a more inferior change in the original rotational center of the hip must be accounted for. Due to these multiple morphological changes, the accurate size of the prosthesis and the cup position are difficult to predict. In comparison with other methods, CT scan-based 3-dimensional templating provides the best accuracy. Despite the presence of anatomic alterations, various types of acetabular and femoral prostheses have been developed to treat hip dysplasia. Both cemented and cementless cups are used in DDH cases. In DDH accompanied by insufficient acetabular bone stock, a cemented cup combined with bone graft provides a reliable treatment. Monoblock stems can be used when the combined anteversion is less than 55°, and a modular stem system when this parameter is greater than 55°. Customized stems can be designed for DDH coupled with severe proximal femoral distortion. A ceramic-on-ceramic bearing is considered optimal for young DDH patients.

Key words: Arthroplasty; Hip dislocation; Leg length inequality; Templating; Total hip replacement

Introduction

Developmental dysplasia of the hip (DDH) is always accompanied by morphological alterations on both the acetabular and femoral sides. On the acetabular side, the acetabulum tends to be smaller and shallower, and a severely dysplastic acetabulum is frequently associated with bone deficiency[1–4]. On the femoral side, excessive femur anteversion, narrower intramedullary canal, malformed anatomy of the proximal femur, and abnormal bony length can occur[2]. In cases of neglected DDH, total hip arthroplasty (THA) is an effective treatment option, but it requires complex preoperative planning[1]. Because the true acetabulum is the ideal place for positioning the cup, the anatomic acetabular location must be determined, and the acetabular bone stock must be evaluated to ensure cup coverage. Measurement of the height of the femur head dislocation aids the maintenance of leg length balance and prevents excessive lengthening of the affected limb. The combined anteversion should be determined to avoid post-surgery dislocation. The present paper summarizes the research on the methodology of measurements of these anatomical deformities performed during the past 5 years. Particular emphasis is placed on the most suitable method to determine the anatomic position of the acetabulum, the accuracy of 3-dimensional (3D) technology for predicting prosthesis size and acetabular bone stock, the safe extent of combined anteversion that prevents dislocation, and bony landmarks to estimate the height of femur head subluxation.

Address for correspondence Jian-guo Liu, MD, PhD, Department of Orthopaedics, Jilin University First Hospital, Changchun, China 130000 Tel: +86-13756661600; Email: liujg6@126.com
Disclosure: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.
Received 30 March 2019; accepted 12 May 2019

In the recent 5 years, patients have been increasingly expecting better restoration of functionality after surgery, and the main reason for patient dissatisfaction after the procedure is perceived leg length discrepancy (LLD). Thus, extensive research has been focused on the LLD, in particular for severely dislocated hips. Postoperative LLD can be a consequence of several factors, such as cup position, inequalities in bony structure, pelvic tilt, and a more inferior change in the original acetabulum. In view of these variables, the present paper addresses the selection of the best strategy for achieving optimal leg length balance in severely dislocated hips.

To provide solutions for different levels of dysplasia, many types of prostheses have been introduced to treat dysplastic hips. For the acetabular side, both cemented and cementless cups have been documented to produce satisfactory results. For the femur side, depending on the degree of combined anteversion and proximal femoral morphology, monoblock stems, modular stems, and customized femoral stems can be chosen. Although modular stems and customized stems are highly expensive, they possess indispensable advantages. Because DDH patients undergo THA surgery at a young age, the selection of an appropriate bearing surface is critical[3]. The ceramic-on-ceramic (CoC) bearing surface has been demonstrated to have the lowest wear rate. As well as low risk of fracture and squeaking, it can be considered the optimal bearing surface for paediatric DDH patients. However, the use of CoC bearing surface is restricted in cases of severely dislocated hips with a shallow and small acetabula.

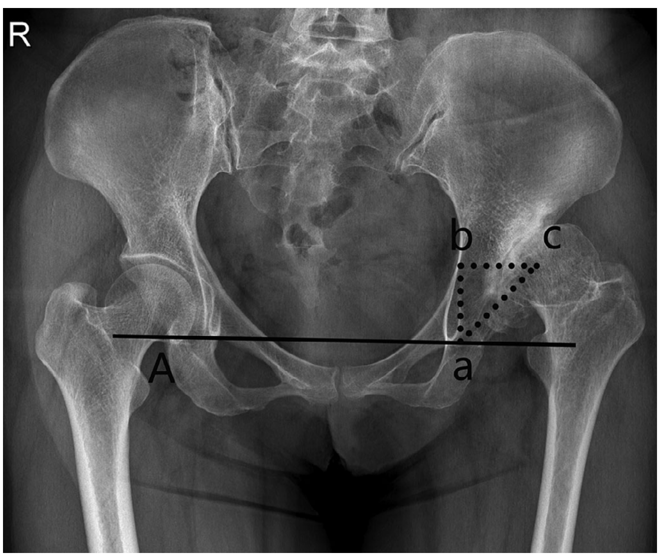

Fig. 1 Ranawat's triangle on an anteroposterior pelvic radiograph. Line A is the inter-teardrop line. Point "a" is located 5 mm lateral to the same side teardrop. Triangle abc (the Ranawat's triangle) is an isosceles right triangle, and the length of ab and bc is equal to 20% of the pelvic height. The triangle delineates the true acetabular area.

Confirmation of Acetabular Position

The true position of the acetabulum is easily confirmed using Ranawat's triangle (Fig. 1) or other methods with anteroposterior pelvic radiographs. However, usually the teardrop on the deformed side in the radiograph is a more convenient marker of the acetabular cup position and is used more frequently in preoperative planning[4,5].

Estimate of Acetabular Bone Stock

Anteroposterior pelvic radiographs and CT images are used to evaluate the acetabular bone stock, and cup coverage can be estimated on postoperative pelvic radiographs (Fig. 2). Some authors demonstrate that 2-dimensional (2D) measurements are not as accurate as 3D[6–8], but whether the former overestimates or underestimates cup coverage is controversial[6,7]. We tend to believe that 2D images overestimate the actual acetabular bone stock, due to the bone shield.

Other authors have applied 3D simulation to analyze acetabular morphology, and report that the bone stock is most insufficient in the superior segment and anterior column of Crowe's hip types III and IV, respectively, compared with normal hips and other Crowe types[5]. It is the consensus that in DDH, THA that do not include bone graft or other cup support techniques require at least 70% cup coverage to avoid

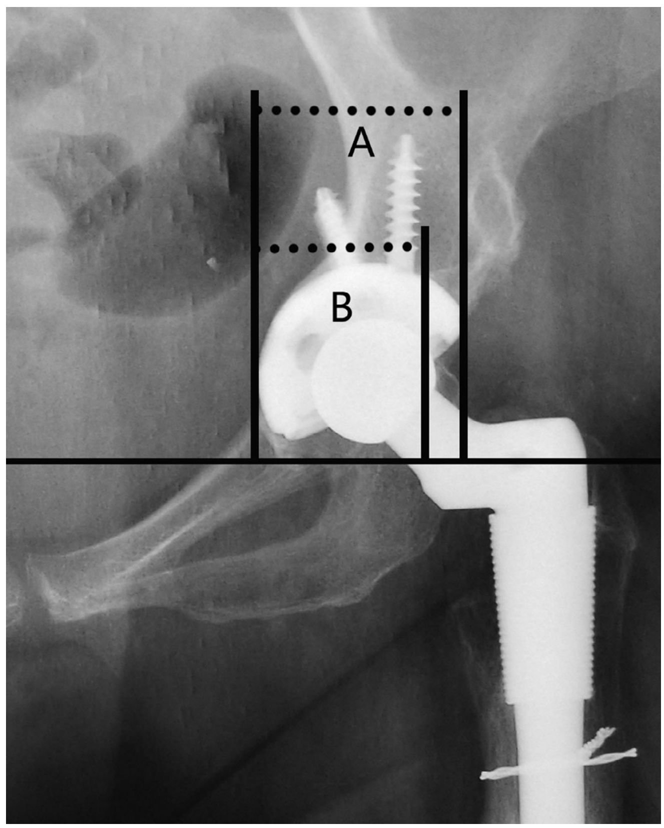

Fig. 2 The 2-dimensional (2D) coverage on anteroposterior radiograph. 2D coverage, % = A/B × 100%. The transverse line is the inter-teardrop line.

failure or complications[1,8]. Nie *et al.*[8] report that a bone graft during surgery is not needed if the line representing the acetabular width on the postoperative anteroposterior pelvic radiograph (i.e. parallel to the teardrop line and tangent to the cup) is at least 35 mm long and the 2D cup coverage is greater than 80%. However, applying this method during preoperative planning is difficult, because the acetabular component size and position must be highly accurate[8].

Lakstein *et al.*[9] analyzed the predictive value of preoperative digital templating and determined that when cup coverage was <65%, 65%–75%, or >75%, then the percentages of hips that required structural support were 100%, 20%, and 10%, respectively. In a mechanical experiment, Tikhilov *et al.*[10] noted that the post-surgical body weight of a patient with DDH is a crucial factor influencing cup stability. Without screw fixation, cup stability could be maintained only when the uncoverage was moderate (15%–25%), while two-screw fixation was needed in cases of significant uncoverage (up to 35%). Percentages greater than this required supporting techniques besides screw fixation[11]. Liu *et al.*[11] point out with the Crowe type III dysplasia hip, reconstructing the hip center at a higher position could gain more cup coverage.

Confirmation of Femur Head Subluxation Height

To measure leg length, most authors use the tip of the lesser trochanter in full-length radiographs as an anatomical marker; the apex of the great trochanter is another option[12,13]. In pelvic anteroposterior radiographs, subluxation height can be easily fixed with a line through the teardrops. For unilateral patients, we can measure the vertical distance from the tip of the lesser trochanter, the apex of the greater trochanter, or the junction of the head–neck to the line through teardrops in both left and right. The difference between the affected and healthy sides can be considered the subluxation height. For bilateral patients, we can only use the vertical distance of each side head–neck junction to the teardrop line as the subluxation (Fig. 3).

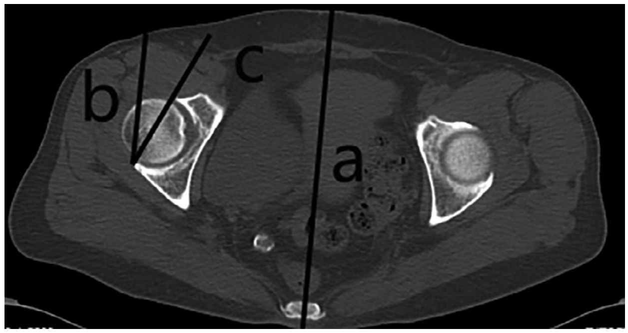

Fig. 4 CT cross-section of affect hip. Line a is the midline of the transverse section of the body. Line c connects the anterior and posterior margins of the right acetabulum. Line b is parallel to line a. The angle formed by b and c is the anteversion of the right acetabulum.

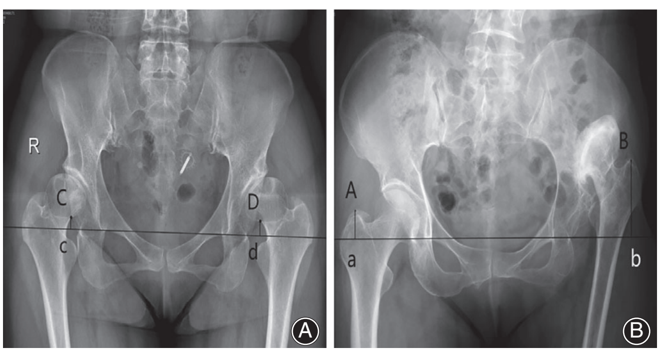

Fig. 3 Anteroposterior pelvic radiographs of patients with developmental dysplasia of the hip (DDH). (A) Bilateral DDH. Cc is the distance from C to teardrop line cd and represents the dislocated height of the right hip. Dd represents the dislocated height of the left hip. (B) Unilateral DDH. Aa is the distance from the tip of the right greater trochanter to the teardrop line ab. Bb is the distance from the tip of the left greater trochanter to the teardrop line. The dislocated height of the left hip is the measured difference between Bb and Aa.

Measurement of the Combined Anteversion

As the severity of DDH increases, acetabular anteversion increases. The acetabular anteversion of Crowe IV DDH is much larger than that of normal hips (33.28° ± 5.98° compared with 20.46° ± 7.48°)[5]. Tetsunaga *et al.*[14] indicate that as the severity of dislocation increases, the femoral anteversion also increases. McKibbin[15] first introduced the concept of combined anteversion. A larger combined anteversion will increase the rate of postoperative dislocation. An appropriate method to deal with overdeveloped acetabular anteversion in DDH is to control the combined anteversion under 55°[16–18]. Even with highly deformed

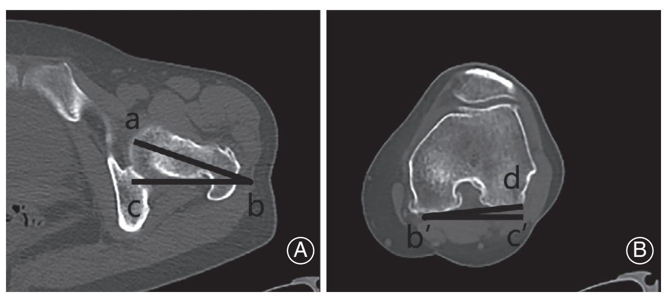

Fig. 5 CT scans of the same side hip (A) and knee (B), taken at the same time and with no change in leg position. (A) Line ab is at the middle of the femur neck and crosses through the center the femoral head. Line bc is the base line and line b′c′ is parallel to it. (B) Line b′d is the posterior condylar line of the femur. The femoral anteversion = angle 1 + angle 2. If the knee has an inward rotational angle according to base line b′c′, its value is negative; if the knee has an outward rotational angle, the value of angle 2 is positive.

acetabula of Crowe IV, it is also a useful method to prevent postoperative dislocation[17]. The preoperative acetabular anteversion can be measured in CT scans (Fig. 4)[17,19]. The angle between the transverse axis of the knee joint and the transverse axis of the femoral neck in CT forms the femoral anteversion (Fig. 5).

Prediction of Prosthesis Size

Some authors have compared the accuracy of digital templating in THA between Crowe type II or III hips and hips with other primary diagnoses. In one study, the predicted cup size of the DDH group was not as accurate as that of the control group (48.8% and 73.2%, respectively), while the predicted stem sizes were comparable (70.8% and 79.2%)[20]. For patients without DDH, Sariali *et al.*[21] compared 3D computerized and 2D digital preoperative planning for accuracy of the prosthesis size used during surgery. They report that the rate of accuracy for predicting the cup or stem size using the 3D technique was significantly higher than that of the 2D technique (100% stem and 96% cup *vs* 43% for both), and the rate for combined components by 3D technique was dramatically higher than for the 2D technique (96% *vs* 16%). CT scan-based 3D templating has also proved an effective method to predict the size of components in THA for hips with dysplasia (estimated in cups and stems as, respectively, 92% and 98%, each within ± one size)[22].

Balance of Leg Length for Severely Dislocated Hips

One of the most common complications after THA of hips with severe dysplasia is leg length discrepancy (LLD), and LLD is a main reason for patient dissatisfaction after surgery. Liu *et al.*[23] notes that for patients with DDH, perceived LLD is a great cause of anxiety and depression, before and after THA. Pei *et al.*[24] report that a postoperative LLD of 10 mm or more in patients with DDH would lead to an asymmetric gait. For patients with DDH types Crowe I or II, LLD can be easily corrected. However, the severe deformities of the acetabulum and proximal femur in Crowe III and IV hips makes correcting leg length balance a complicated process, which needs to be decided before surgery.

According to Li *et al.*[13], there are three types of LLD in patients with DDH: bony, anatomical, or functional (Fig. 6). A bony LLD is caused by a difference in absolute leg lengths between the two legs. An anatomical LLD is produced by a different level of dislocation in each leg. A functional LLD is experienced subjectively by the patient while in a standing position. Balancing the leg length for a patient with DDH can be complicated and challenging because of the many factors that can affect the leg length in hip dysplasia, such as the height of dislocation, pelvic tilt, pelvic imbalance, and the height of acetabular components. Corrections must be chosen on a case-by-case basis.

Li *et al.*[13] stratified patients with DDH as either unilateral or bilateral dysplasia, with each comprising three subtypes based on pelvic tilt, and each subtype with its own leg length balance strategy. Briefly, under the precondition of true acetabular reconstruction, whether unilateral or bilateral, if no fixed pelvic tilt is shown, then anatomical LLD should be applied during THA. Otherwise, functional LLD should be the first choice to balance leg length. This strategy is

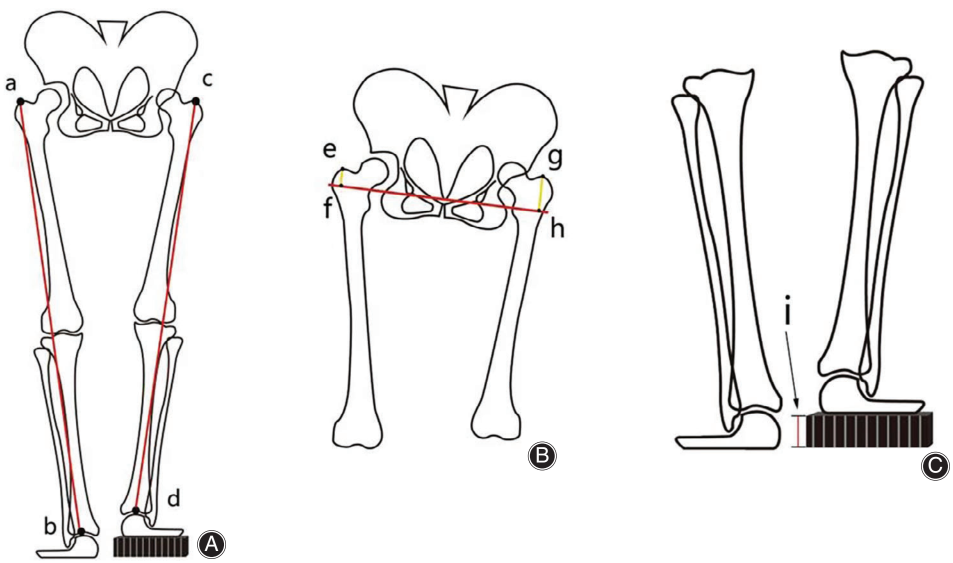

Fig. 6 Schematic diagram illustrating three different types of leg length discrepancy: bony (A), anatomical (B), and functional (C). (A) ab and cd represent bony leg length (from the tip of greater trochanter to midpoint of ankle) for the two legs. ab – cd = bony leg length discrepancy (LLD). (B) Line fh is the inter-teardrop line. Points e and g correspond to the tips of the greater trochanter. gh – ef = functional LLD. (C) When developmental dysplasia of the hip (DDH) patients stand straight, a block is placed under the leg and the block height is raised until DDH patients feel fit. At that moment, the height of the block is measured as length i. i is the functional LLD.

based on the condition that the bony lengths of the two legs are the same. The research by Li *et al.*[13] included only cases with an overall significant bony LLD of 3.5 mm.

However, Zhang *et al.*[25] found that 78% of patients with unilateral DDH have a greater lesser trochanter–tibial plafond distance in the dislocated side compared with the healthy side, whose average value is 10.0 mm (range, 0.3–28.8 mm). Therefore, full-length radiographic examination should be considered as standard in preoperative planning, as it can reveal a bony LLD. Although the bony LLD is usually too small to consider during preoperative planning, some patients with severe DDH can have a bony LLD of 2 cm or more. Overlooking these bony LLD may lead to worse outcomes for these patients.

Bilgen *et al.*[26] divided unilateral pelvic dysplasia into three areas with the following four lines: connecting the apexes of the iliac wings; through the acetabular teardrops; connecting the inferior sacroiliac joints; and connecting the lowest points of the ischial tuberosity. They thus determined that the teardrop line may not be the most appropriate to guide the position of the acetabular component or to calculate the LLD. This is because the teardrop of the dysplasia side is more distal compared with the healthy side, with mean distances for Crowe types II, III, and IV of 5, 8, and 10.56 mm, respectively. The authors concluded that a line parallel to the line which connects the inferior sacroiliac joints and crosses the teardrop of the healthy side could be more useful[26].

Cemented Cups

Cemented acetabular components without bone graft in DDH are reported to have a high revision rate[4,27–29]. According to Dapuzzo and Sierra[4], when cemented cups were combined with autogenous bone graft the revision rate was satisfactory for approximately 10 years post-surgery, but these rates increased dramatically after 10 years due to graft collapse or socket loosening. However, Oe *et al.*[30] reported combining cemented cups with three types of bulk bone graft to treat dysplasia hips, with no signs of cup loosening, and no cup required revision after at least 10 years of follow-up. Pizarro *et al.*[31] also used cemented cups combined with bulk bone graft to treat dysplasia hips, and after a mean 8 years found no signs of graft collapse or cup loosening. Maruyama *et al.*[32] used cemented cup combined with bulk bone and impaction bone grafting to treat dysplasia hips. After 10 ± 3 years follow-up, only one cup (1%) needed revision due to loosening, and no resorption signs were observed. Colo *et al.*[33] used cemented cups combined with impact bone graft to treat 24 dysplasia hips, and after an average of 20 years, only three cups needed revision: one, to release the sciatic nerve, and two due to aseptic loosening at 12 and 26 years.

Cementless Cups

The utility of cementless acetabular components to treat DDH has been widely reported and with satisfying results. Takigami *et al.*[34] used Spongiosa Metal II cups to treat 81 dysplasia hips and no cup revision was needed, after an average of 6.4 years and at least 5 years follow-up. Kamada *et al.*[35] used cementless tantalum modular acetabular cups to treat 45 dysplasia hips and no cup revision was needed after a mean of 9.8 years follow-up. Ollivier *et al.*[36] treated 28 Crowe IV dysplasia hips with cementless prostheses combined with transverse subtrochanteric osteotomy. After an average of 10 years follow-up, only 5 hips were revised (two cups, two stems, and one liner exchange).

Monoblock Stems

Taniguchi *et al.*[37] reported that stem anteversion after THA with a tapered wedge stem was greater, and over a greater range, compared with a metaphyseal filling stem. Therefore, these stems may not be suitable for severe DDH with a larger combined anteversion. In a study of 198 patients with dysplasia hips, Kato *et al.*[38] evaluated a modified extensively porous-coated cylindrical stem that relied on distal fixation. After 12 years' follow-up, only 3 hips were revised due to polyethylene liner wear, and 1 of them was accompanied with cup-related osteolysis that was solved by bone grafting. Ozden *et al.*[39] noted that, for patients with high hip dislocated DDH, the rates for 10-year survival and complications associated with a cylindrical two-third coated stem were significantly better than those of the proximal one-third coated stem (Fig. 7). In the study by Faldini *et al.*[40], 34 hips were treated with a Wagner cone prosthesis, and the mean follow-up was 12 years; no loose prosthesis was observed, and no revision was necessary. Parry *et al.*[41] also note that the Wagner cone stem is a good choice to deal with a challenging femur in primary hip arthroplasty, including for DDH.

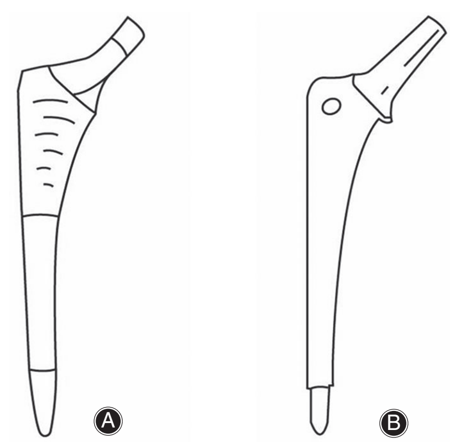

Fig. 7 Plane graphs of two types of monoblock stems. (A) A proximal-coated stem. (B) An extensively coated stem. The use of the extensively coated stem to treat high-dislocated dysplasia hips could provide a better 10-year survival and complication rate than proximal-coated stems.

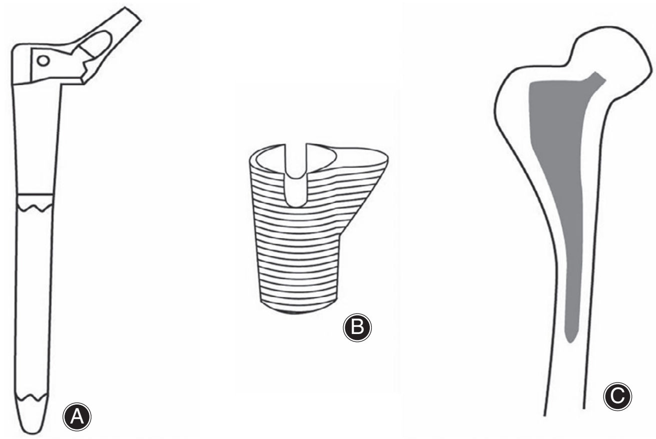

Fig. 8 Plane graphs of S-ROM prosthesis (A and B) and customized stem. (A) The stem of S-ROM prosthesis. (B) The sleeve of S-ROM prosthesis. The stem anteversion can be set freely and precisely when the stem and the sleeve and put together. (C) A customized stem. Despite its high price, complicated production process, and difficult insertion procedure, customized femoral implants fit the malformed femoral medullary cavity better.

Modular Stems

With a modular stem, the stem anteversion can be set freely and precisely according to the angle we need. Peters *et al.*[42] predicted the utility of the modular stem with plain films, and concluded that a modular stem should be used during surgery if the neck-shaft angle in anteroposterior radiographs is >142°, the lateral neck-shaft angle is <153°, and the calculated femoral anteversion is >32°. Rollo *et al.*[43] treated 17 Crowe type IV DDH with subtrochanteric femoral shortening osteotomy, in which S-ROM (Fig. 8A,B) and CSR Japan stems were used in 12 and 5 hips, respectively. After a mean follow-up of 88 months, none of these stems needed revision.

Wang *et al.*[44] studied 76 high dislocated hips treated with transverse subtrochanteric shortening osteotomy and S-ROM stem. During the mean 10-year follow-up, 3 hips (3.9%) dislocated immediately after surgery, all of which underwent successful closed reduction and plaster bandage fixation and never reoccurred. Only one loose stem needed revision surgery by the latest follow-up, which was mostly due to a short neck and poor bone quality. To treat DDH hips, Tamegai *et al.*[45] used a modified S-ROM stem that was designed especially for Asians; namely, the S-ROM-A. It has a shorter stem length and the neck taper size is reduced from 11/13 to 9/10. None of the 220 hips needed revision, but the mean follow-up was only 3.3 years.

The S-ROM stem may not be optimal in severely dislocated DDH. With 3D reconstruction of the proximal femur based on CT data, Liu *et al.*[46] found that the proximal femur medullary cavities of patients with DDH were narrower than those of normal (control) hips, mainly around the lesser trochanter level. This led to a chimney-like shape of the Crowe IV proximal femur cavity, which did not match the S-ROM metaphyseal canal flare.

Benazzo *et al.*[47] used a special modular cementless system to treat 143 patients with DDH (169 hips). With this modular system, stem size, offset, anteversion, and neck length are completely adjustable. During 8 years of follow-up, only 2 stems needed revision, for periprosthetic fracture and stem subsidence, respectively.

Customized Femoral Prosthesis

Severe proximal femoral distortions have become obstacles for using classical industry-designed stems, which cannot be matched with on-shelf stems in preoperative planning. In these cases, customized femoral implants may fit the proximal femoral anatomy better (Fig. 8C). The utility of custom-made implants should conform to the principles of computer-aided design, engineering, and manufacturing (combined anteversions D, E, and M, respectively). Therefore, a highly elaborate preoperative plan is critical, including comprehensive X-ray examination, CT evaluation, 3D reconstruction, and fine matching of designed stems.

Although the main surgical procedures of custom-made implants are very similar to those for classical implants, three points should be emphasized. First, the shape of the femoral canal must match the stem, and the cancellous bone of the proximal femur should be reserved as much as possible. Second, in cases in which the stem anteversion is >45°, de-rotational osteotomy may be a better choice to correct the severity of the anteversion together with designed stems. Finally, choices of acetabular reconstructions are individualized procedures, which mean surgeons can choose acetabular reconstruction methods and implants freely[48–50].

Bearing Surface

Baki *et al.*[51] used metal-on-metal (MoM) components to treat 27 mid or high dislocations of the hip, and during an average 34 months of follow-up, no revision was required. Nevertheless, particles due to wear of the MoM bearings limit their application. Although Lübbeke *et al.*[52] reported that the all-cause revision rates associated with MoM and ceramic-on-polyethylene (CoP) within the first 10 years were comparable, after 10 years that of the MoM was significantly higher. Kleeman *et al.*[53] also showed that MoM bearings result in a higher revision rate (5.28%) compared with metal-on-polyethylene (MoP; 4.28%) or CoP (3.52%). In the meta-analysis of Lee *et al.*[54], the revision rate for all-reason, aseptic loosening, or periprosthetic joint infection with MoM was higher than that of CoC. This was in accord with the study result of Hu *et al.*[55]. To our knowledge, CoC bearings have a lower wear rate than do MoP or CoP[56–58]. Sentuerk *et al.*[59] reported that CoC, with the lowest wear rate and ability to control fracture and squeaking risk, should be an excellent choice for the young active patient undergoing THA.

Restriction of Surface Bearing Choices

Acetabula with dysplasia are always shallow and small, and these deformities will become more severe with the increasing dysplasia level of the hip. Therefore, THA for high dislocated hips can encounter an especially small acetabulum, which makes using normal size cups and heads a challenge. Yet, cups and heads of smaller size will jeopardize hip stability, and limit the polyethylene thickness and utility of CoC bearings (which requires a 44-mm minimum cup size). Xu *et al.*[60] introduced a method using normal sized cups (≥44 mm) to treat high dislocated hips. With the help of preoperative 3D simulation, they positioned the cups posterosuperiorly. Thus, 11 of 13 hips were treated with 44-mm cups and the other two hips were treated with 46-mm cups.

Conclusion

Preoperative planning is a challenging and essential process for THA with DDH. All potential morphological changes should be revealed before surgery. In most situations, acetabular construction is the gold standard, so the anatomic position of the acetabulum should be confirmed. Whether cup support techniques are needed is decided based on the acetabular bone stock. The height of the dislocation of the femoral head is a key factor to predict leg length after THA and is important for a leg length balance strategy. If the height of dislocation is more than 3.5 cm, osteotomy is considered to help reduction and protect the sciatic nerve. Both acetabular and femur anteversion may be more than the normal range. Controlling a combined anteversion that is less than 55° is an effective way to avoid dislocation after surgery. For hips with severe morphological changes, CT-based 3D templating is the best way to predict the size of the prosthesis. An integrated leg length balance strategy should take into consideration the three types of LLD, pelvic tilt, pelvic imbalance, and cup position.

The choice of prosthesis is made after measurement of the combined anteversion and observation of the proximal femur morphology. For young and active patients with DDH, CoC is the optimal bearing surface. However, a shallow and small anatomic acetabulum restricts its use.

References

1. Rogers BA, Garbedian S, Kuchinad RA, Backstein D, Safir O, Gross AE. Total hip arthroplasty for adult hip dysplasia. J Bone Joint Surg Am, 2012, 94: 1809–1821.
2. Perry KI, Berry DJ. Femoral considerations for total hip replacement in hip dysplasia. Orthop Clin North Am, 2012, 43: 377–386.
3. Greber EM, Pelt CE, Gililland JM, Anderson MB, Erickson JA, Peters CL. Challenges in total hip arthroplasty in the setting of developmental dysplasia of the hip. J Arthroplasty, 2017, 32: S38–S44.
4. Dapuzzo MR, Sierra RJ. Acetabular considerations during total hip arthroplasty for hip dysplasia. Orthop Clin North Am, 2012, 43: 369–375.
5. Yang Y, Zuo J, Liu T, Xiao J, Liu S, Gao Z. Morphological analysis of true acetabulum in hip dysplasia (Crowe Classes I–IV) via 3-D implantation simulation. J Bone Joint Surg Am, 2017, 99: e92.
6. Xu J, Qu X, Li H, Mao Y, Yu D, Zhu Z. Three-dimensional host bone coverage in Total hip arthroplasty for Crowe types II and III developmental dysplasia of the hip. J Arthroplasty, 2017, 32: 1374–1380.
7. Wang L, Thoreson AR, Trousdale RT, Morrey BF, Dai K, An KN. Two-dimensional and three-dimensional cup coverage in total hip arthroplasty with developmental dysplasia of the hip. J Biomech, 2013, 46: 1746–1751.
8. Nie Y, Pei F, Shen B, Kang P, Li Z. Implication of acetabular width on the anteroposterior pelvic radiograph of patients with developmental dysplasia of the hip. J Arthroplasty, 2015, 30: 489–494.
9. Lakstein D, Tan Z, Oren N, Mäkinen TJ, Gross AE, Safir O. Preoperative planning of total hip arthroplasty on dysplastic acetabuli. Hip Int, 2017, 27: 55–59.
10. Tikhilov R, Shubnyakov I, Burns S, *et al.* Experimental study of the installation acetabular component with uncoverage in arthroplasty patients with severe developmental hip dysplasia. Int Orthop, 2016, 40: 1595–1599.
11. Liu B, Gao YH, Ding L, Li SQ, Liu JG, Qi X. Computed tomographic evaluation of bone stock in patients with Crowe type III developmental dysplasia of the hip: implications for guiding acetabular component placement using the high hip center technique. J Arthroplasty, 2018, 33: 915–918.
12. Takao M, Ohzono K, Nishii T, Miki H, Nakamura N, Sugano N. Cementless modular total hip arthroplasty with subtrochanteric shortening osteotomy for hips with developmental dysplasia. J Bone Joint Surg Am, 2011, 93: 548–555.
13. Li Y, Zhang X, Wang Q, *et al.* Equalisation of leg lengths in total hip arthroplasty for patients with Crowe type-IV developmental dysplasia of the hip: classification and management. Bone Joint J, 2017, 99: 872–879.
14. Tetsunaga T, Fujiwara K, Endo H, *et al.* Calcar Femorale in patients with osteoarthritis of the hip secondary to developmental dysplasia. Clin Orthop Surg, 2017, 9: 413–419.
15. McKibbin B. Anatomical factors in the stability of the hip joint in the newborn. J Bone Joint Surg Br, 1970, 52: 148–159.
16. Zhang J, Wang L, Mao Y, Li H, Ding H, Zhu Z. The use of combined anteversion in total hip arthroplasty for patients with developmental dysplasia of the hip. J Arthroplasty, 2014, 29: 621–625.
17. Zhu B, Su C, He Y, *et al.* Combined anteversion technique in total hip arthroplasty for Crowe IV developmental dysplasia of the hip. Hip Int, 2017, 27: 589–594.
18. Imai H, Miyawaki J, Kamada T, Takeba J, Mashima N, Miura H. Preoperative planning and postoperative evaluation of total hip arthroplasty that takes combined anteversion. Eur J Orthop Surg Traumatol, 2016, 26: 493–500.
19. Tönnis D, Heinecke A. Acetabular and femoral anteversion: relationship with osteoarthritis of the hip. J Bone Joint Surg Am, 1999, 81: 1747–1770.
20. Zhao X, Zhu ZA, Zhao J, *et al.* The utility of digital templating in Total hip arthroplasty with Crowe type II and III dysplastic hips. Int Orthop, 2011, 35: 631–638.
21. Sariali E, Mauprivez R, Khiami F, Pascal-Mousselard H, Catonné Y. Accuracy of the preoperative planning for cementless total hip arthroplasty. A randomised comparison between three-dimensional computerised planning and conventional templating. Orthop Traumatol Surg Res, 2012, 98: 151–158.
22. Inoue D, Kabata T, Maeda T, *et al.* Value of computed tomography-based three-dimensional surgical preoperative planning software in total hip arthroplasty with developmental dysplasia of the hip. J Orthop Sci, 2015, 20: 340–346.
23. Liu R, Li Y, Fan L, Mu M, Wang K, Song W. Depression and anxiety before and after limb length discrepancy correction in patients with unilateral developmental dysplasia of the hip. J Psychosom Res, 2015, 79: 574–579.
24. Chen G, Nie Y, Xie J, Cao G, Huang Q, Pei F. Gait analysis of leg length discrepancy-differentiated hip replacement patients with developmental dysplasia: a midterm follow-up. J Arthroplasty, 2018, 33: 1437–1441.
25. Zhang Z, Luo D, Cheng H, Xiao K, Zhang H. Unexpected long lower limb in patients with unilateral hip dislocation. J Bone Joint Surg Am, 2018, 100: 388–395.
26. Bilgen ÖF, Salar N, Bilgen MS, Mutlu M, Kara GK, Gürsel E. The effect of dislocation type (Crowe types I-IV) on pelvic development in developmental dysplasia of the hip: a radiologic study of anatomy. J Arthroplasty, 2015, 30: 875–878.
27. Sakellariou VI, Christodoulou M, Sasalos G, Babis GC. Reconstruction of the acetabulum in developmental dysplasia of the hip in total hip replacement. Arch Bone Jt Surg, 2014, 2: 130–136.
28. MacKenzie JR, Kelley SS, Johnston RC. Total hip replacement for coxarthrosis secondary to congenital dysplasia and dislocation of the hip. Long-term results. J Bone Joint Surg Am, 1996, 78: 55–61.
29. Numair J, Joshi AB, Murphy JC, Porter ML, Hardinge K. Total hip arthroplasty for congenital dysplasia or dislocation of the hip. Survivorship analysis and long-term results. J Bone Joint Surg Am, 1997, 79: 1352–1360.
30. Oe K, Iida H, Kawamura H, *et al.* Long-term results of acetabular reconstruction using three bulk bone graft techniques in cemented total hip arthroplasty for developmental dysplasia. Int Orthop, 2016, 40: 1949–1954.

31. Pizarro FC, Young SW, Blacutt JH, Mojica R, Cruz JC. Total hip arthroplasty with bulk femoral head autograft for acetabular reconstruction in developmental dysplasia of the hip. ISRN Orthop, 2013, 2013: 794218.
32. Maruyama M, Wakabayashi S, Ota H, Tensho K. Reconstruction of the shallow acetabulum with a combination of autologous bulk and impaction bone grafting fixed by cement. Clin Orthop Relat Res, 2017, 475: 387–395.
33. Colo E, Rijnen WH, Gardeniers JW, van Kampen A, Schreurs BW. Satisfying results of primary hip arthroplasty in patients with hip dysplasia at a mean followup of 20 years. Clin Orthop Relat Res, 2016, 474: 2462–2468.
34. Takigami I, Ito Y, Matsumoto K, Ogawa H, Terabayashi N, Shimizu K. Primary total hip arthroplasty with a spongy metal surface acetabular component for hip dysplasia. J Arthroplasty, 2013, 28: 172–177.
35. Kamada T, Mashima N, Nakashima Y, Imai H, Takeba J, Miura H. Mid-term clinical and radiographic outcomes of porous tantalum modular acetabular components for hip dysplasia. J Arthroplasty, 2015, 30: 607–610.
36. Ollivier M, Abdel MP, Krych AJ, Trousdale RT, Berry DJ. Long-term results of total hip arthroplasty with shortening subtrochanteric osteotomy in Crowe IV developmental dysplasia. J Arthroplasty, 2016, 31: 1756–1760.
37. Taniguchi N, Jinno T, Koga D, Hagino T, Okawa A, Haro H. Cementless hip stem anteversion in the dysplastic hip: a comparison of tapered wedge vs metaphyseal filling. J Arthroplasty, 2017, 32: 1547–1552.
38. Kato T, Otani T, Sugiyama H, Hayama T, Katsumata S, Marumo K. Cementless total hip arthroplasty in hip dysplasia with an extensively porous-coated cylindrical stem modified for Asians: a 12-year follow-up study. J Arthroplasty, 2015, 30: 1014–1018.
39. Ozden VE, Dikmen G, Beksac B, Tozun IR. Tapered stems one-third proximally coated have higher complication rates than cylindrical two-third coated stems in patients with high hip dislocation undergoing total hip arthroplasty with step-cut shortening osteotomy. Orthop Traumatol Surg Res, 2017, 103: 569–577.
40. Faldini C, Miscione MT, Chehrassan M, *et al.* Congenital hip dysplasia treated by total hip arthroplasty using cementless tapered stem in patients younger than 50 years old: results after 12-years follow-up. J Orthop Traumatol, 2011, 12: 213–218.
41. Parry MC, Vioreanu MH, Garbuz DS, Masri BA, Duncan CP. The Wagner cone stem for the management of the challenging femur in primary hip arthroplasty. J Arthroplasty, 2016, 31: 1767–1772.
42. Peters CL, Chrastil J, Stoddard GJ, Erickson JA, Anderson MB, Pelt CE. Can radiographs predict the use of modular stems in developmental dysplasia of the hip?. Clin Orthop Relat Res, 2016, 474: 423–429.
43. Rollo G, Solarino G, Vicenti G, Picca G, Carrozzo M, Moretti B. Subtrochanteric femoral shortening osteotomy combined with cementless total hip replacement for Crowe type IV developmental dysplasia: a retrospective study. J Orthop Traumatol, 2017, 18: 407–413.
44. Wang D, Li LL, Wang HY, Pei FX, Zhou ZK. Long-term results of cementless total hip arthroplasty with subtrochanteric shortening osteotomy in Crowe type IV developmental dysplasia. J Arthroplasty, 2017, 32: 1211–1219.
45. Tamegai H, Otani T, Fujii H, Kawaguchi Y, Hayama T, Marumo K. A modified S-ROM stem in primary total hip arthroplasty for developmental dysplasia of the hip. J Arthroplasty, 2013, 28: 1741–1745.
46. Liu S, Zuo J, Li Z, *et al.* Study of three-dimensional morphology of the proximal femur in developmental adult dysplasia of the hip suggests that the on-shelf modular prosthesis may not be an ideal choice for patients with Crowe type IV hips. Int Orthop, 2017, 41: 707–713.
47. Benazzo FM, Piovani L, Combi A, Perticarini L. Modulus stem for developmental hip dysplasia: long-term follow-up. J Arthroplasty, 2015, 30: 1747–1751.
48. Tsiampas DT, Pakos EE, Georgiadis GC, Xenakis TA. Custom-made femoral implants in total hip arthroplasty due to congenital disease of the hip: a review. Hip Int, 2016, 26: 209–214.
49. Pakos EE, Stafilas KS, Tsovilis AE, Vafiadis JN, Kalos NK, Xenakis TA. Long term outcomes of total hip arthroplasty with custom made femoral implants in patients with congenital disease of hip. J Arthroplasty, 2015, 30: 2242–2247.
50. Flecher X, Parratte S, Aubaniac JM, Argenson JN. Three-dimensional custom-designed cementless femoral stem for osteoarthritis secondary to congenital dislocation of the hip. J Bone Joint Surg Br, 2007, 89: 1586–1591.
51. Baki ME, Timurkaynak A, Aydın H, Baki C. Metal-on-metal dysplasia cup total hip arthroplasty for hip osteoarthritis secondary to developmental dysplasia of the hip. Eklem Hastalik Cerrahisi, 2014, 25: 154–157.
52. Lübbeke A, Gonzalez A, Garavaglia G, *et al.* A comparative assessment of small-head metal-on-metal and ceramic-on-polyethylene total hip replacement. Bone Joint J, 2014, 96: 868–875.
53. Kleeman LT, Bala A, Penrose CT, Seyler TM, Wellman SS, Bolognesi MP. Comparison of postoperative complications following metal-on-metal total hip arthroplasty with other hip bearings in medicare population. J Arthroplasty, 2018, 33: 1826–1832.
54. Lee YK, Yoon BH, Choi YS, Jo WL, Ha YC, Koo KH. Metal on metal or ceramic on ceramic for cementless total hip arthroplasty: a meta-analysis. J Arthroplasty, 2016, 31: 2637–2645.e1.
55. Hu D, Tie K, Yang X, Tan Y, Alaidaros M, Chen L. Comparison of ceramic-on-ceramic to metal-on-polyethylene bearing surfaces in total hip arthroplasty: a meta-analysis of randomized controlled trials. J Orthop Surg Res, 2015, 10: 22.
56. Higuchi Y, Hasegawa Y, Seki T, Komatsu D, Ishiguro N. Significantly lower wear of ceramic-on-ceramic bearings than metal-on-highly cross-linked polyethylene bearings: a 10- to 14-year follow-up study. J Arthroplasty, 2016, 31: 1246–1250.
57. Atrey A, Wolfstadt JI, Hussain N, *et al.* The ideal total hip replacement bearing surface in the young patient:A prospective randomized trial comparing alumina ceramic-on-ceramic with ceramic-on-conventional polyethylene:15-Year follow-up. J Arthroplasty, 2018, 33: 1752–1756.
58. Beaupre LA, Al-Houkail A, Johnston DWC. A randomized trial comparing ceramic-on-ceramic bearing vs ceramic-on-crossfire-polyethylene bearing surfaces in total hip arthroplasty. J Arthroplasty, 2016, 31: 1240–1245.
59. Sentuerk U, von Roth P, Perka C. Ceramic on ceramic arthroplasty of the hip: new materials confirm appropriate use in young patients. Bone Joint J, 2016, 98: 14–17.
60. Xu J, Xu C, Mao Y, Zhang J, Li H, Zhu Z. Posterosuperior placement of a standard-sized cup at the true acetabulum in acetabular reconstruction of developmental dysplasia of the hip with high dislocation. J Arthroplasty, 2016, 31: 1233–1239.