Accuracy of Cup Positioning with the CT-Based 2D-3D Matched Navigation System: A Prospective, Randomized and Controlled Study

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Abstract

Background: The accuracy of various navigation systems used for total hip arthroplasty has been described, but no publications reported the accuracy of cup orientation in CT-based 2D-3D matched navigation.

Methods: In a prospective randomized controlled study, 80 hips including 44 with developmental dysplasia of the hip (DDHs) were divided into a CT-based 2D-3D matched navigation group (2D-3D group) and a paired-point matched navigation group (PPM group). The accuracy of cup orientation (absolute difference between the intraoperative record and the postoperative measurement) was compared between groups. Additionally, multiple logistic regression analysis was performed to evaluate patient factors affecting the accuracy of cup orientation in each navigation.

Results: The accuracy of cup inclination was 2.5° ± 2.2° in the 2D-3D group and 4.6° ± 3.3° in the PPM group (P = 0.0016). The accuracy of cup anteversion was 2.3° ± 1.7° in the 2D-3D group and 4.4° ± 3.3° in the PPM group (P = 0.0009). In the PPM group, the presence of roof osteophytes decreased the accuracy of cup inclination (odds ratio 8.27, P = 0.0140) and the absolute value of pelvic tilt had a negative influence on the accuracy of cup anteversion (odds ratio 1.27, P = 0.0222). In the 2D-3D group, patient factors had no effect on the accuracy of cup orientation.

Conclusion: The accuracy of cup positioning in CT-based 2D-3D matched navigation was better than in paired-point matched navigation, and was not affected by patient factors. It is a useful system for even severely-deformed pelvises such as DDHs.

Introduction

Acetabular cup position is an important factor affecting both the early and long-term outcomes of total hip arthroplasty (THA). Inadequate orientation of the acetabular component has been associated with post-operative complications such as impingement [1], dislocation [2], and accelerated polyethylene wear [3].

Freehand techniques and the use of mechanical alignment guides have been described as means for achieving correct placement of the acetabular component. However, these methods can result in inaccuracy of cup inclination and anteversion [4-7]. Navigation systems have been reported to increase the accuracy of cup orientation in THA for over two decades since the 1990s [8-10].

Computer-assisted hip navigation systems are classified into three groups; CT-based, fluoroscopic, and imageless navigation [11]. Moreover, CT-based navigation systems are divided into three types depending on registration methods; paired-point matching, surface matching, and 2D-3D matching registration [12]. In paired-point and surface matching registration, the surgeon has to match the surface shapes during surgery to the patient's anatomical landmarks reconstructed from preoperative CT images, while in 2D-3D matching registration, multidirectional fluoroscopic images taken during surgery have to be matched to three-dimensional pelvic images reconstructed from preoperative CT data [13].

CT is the most accurate tool to evaluate acetabular cup orientation [14]. However, there have been only a few studies describing the accuracy of CT-based navigated cup position by postoperative CT measurement [15, 16]. Furthermore, no study confirmed the accuracy of acetabular component orientation in CT-based 2D-3D matching navigation THA.

Secondary osteoarthritis (OA) caused by developmental dysplasia of the hip (DDH) has a high prevalence among hip OA joints in Japan [17]. In our institution, CT-based paired-point matched navigation was introduced in 2005, and CT-based 2D-3D matched navigation has also been used since 2010. We have performed many THAs involving severely deformed pelvises using CT-based navigation systems. In our experience, we have realized the usefulness of CT-based 2D-3D matched navigation systems in patients with abnormal anatomy (Fig. 1). We then hypothesised that 2D-3D matching registration would have an advantage with regard to the accuracy of acetabular cup orientation over paired-point matching registration. The purpose of this prospective randomized controlled study was to compare the accuracy of cup position in primary THA between CT-based 2D-3D matched navigation and CT-based paired-point matched navigation. No clinical study on the accuracy of cup orientation using CT-based 2D-3D matched navigation has been reported. The result of this study will provide a new insight into the optimal method.

Materials and Methods

Study Design and Patient Selection

Between September 2015 and January 2017, we performed a prospective, randomized, controlled study of two groups of forty patients each. The study was approved by our institution's ethics committee (approval No. 1508-008) and was conducted in accordance with ethical standards of the 1964 Declaration of Helsinki as revised in 1983 and 2000. All patients were informed about the study in exact detail. Written informed consent was obtained from every patient. The patient inclusion criteria were: primary or secondary osteoarthritis, or osteonecrosis of the femoral head, and an age of more than 20 years old (Table 1). The exclusion criteria were revision THA. We performed block randomization of all patients to a CT-based 2D-3D matched navigation group (2D-3D group) or a CT-based paired-point matched navigation group (PPM group) according to a random number list generated by SPSS version 20.0 (SPSS Inc., Chicago, IL, USA).

Devices and Surgical Procedure

We used a CT-based navigation system (Vector Vision hip CT-based ver. 3.5.2, BrainLab, Heimstetten, Germany). Operators set the registration method for either 2D-3D matching or paired-point matching registration in this navigation system in accordance with random allocation. Preoperative CT images were taken from pelvis to knee joint using a multi-slice CT scanner (Discovery CT750HD; GE Medical Systems, Milwaukee, WI, USA). Imaging settings were as follows: tube voltage 120 kV; tube current 150 mA; slice thickness 2 mm; and slice pitch 2 mm. CT image data saved in DICOM format were transferred into the navigation system for preoperative planning and intraoperative registration. In the planning module, the anterior pelvic plane (APP) consisting of bilateral anterior superior iliac spines (ASIS) and pubic tubercles was identified.

Cementless titanium hemisphere cups (AMS HA, Kyocera Medical, Osaka, Japan) were used. The operations were performed by three orthopaedic surgeons (HE, TT, KF) with experience of over 300 navigated THAs each. Before the surgery, two 4-mm diameter Schantz screws were inserted into the ipsilateral iliac crest approximately 5 mm proximal to the ASIS percutaneously through stab incisions with the patient supine. A T-shaped reference array with three infrared reflection spheres was then fixed to the Schantz screws.

In the 2D-3D group, before the surgery, two fluoroscopic pelvic images taken from different angles of more than 20° were obtained using a mobile fluoroscopy system (Flexi View 8800; GE Medical Systems) with the patient supine. We took these images so that they contained the pubic tubercles and bilateral obturator foramens. Mean irradiation time was only a few seconds. After acquisition of these images, one point on the ASIS and two points on the iliac crest on the affected side were registered by direct palpation of these bony landmarks through stub incisions made for Scahntz screw insertion using the pointer. Finally, fluoroscopic images were matched to the three-dimensional pelvic images reconstructed from preoperative CT data (Fig. 2).

In the PPM group, prior to the operation, one point on the ASIS and four points on the iliac crest were acquired for registration in the same way as in the 2D-3D group. The surgery was begun after changing the patient's position from supine to the lateral decubitus position. Following resection of the femoral head and acetabular exposure, one point on the ilium, four points on the acetabular edge, and seven points inside the acetabulum were directly palpated with the pointer. The registration was then completed.

At surgery, all patients were placed in the lateral decubitus position. Surgical approaches were selected by the surgeons depending on the degree of each patient's pelvic deformity, joint contracture, and leg length discrepancy (Table 1). The accuracy of CT-based navigation did not depend on the surgical approach [18]. After reaming of the acetabulum, fixation of the cup was achieved by press-fit impaction and then additional screws were inserted in all patients under guidance by the navigation system. The final inclination and anteversion of the acetabular component were measured by the surgeons who palpated five points on the outer edge of the cup using the pointer. The measurement was carried out three times. Average values of the three measurements were recorded as intraoperative inclination and anteversion angles. On the screen of both navigation systems, cup angles were shown in the operative definition [19].

Postoperative Management and Evaluations

The postoperative protocols were the same in both groups, with full weight-bearing recommended as tolerated from the day following the date of surgery. For postoperative evaluation, CT images from the pelvis to the knee joint were taken one week after surgery. CT image data saved in DICOM format were transferred into 3D templating software ver. 03.08.05 (Kyocera Medical). Firstly, the pelvic coordinate system was set to the APP on the coronal plane. The sagittal and axial planes were then defined as those perpendicular to the APP (Fig. 3). In accordance with the definition of Murray [19], the radiographic inclination angle was measured by identifying the largest cup diameter on the coronal plane (Fig. 4A). In a similar way, the anatomical anteversion angle was calculated on the axial plane (Fig. 4B). All measurements were performed three times by three orthopaedic surgeons (KY, YF, TM) and averaged. In the current study, all cup angles were represented as the radiographic values using the algorithm of Murray [19]. The absolute difference between the intraoperative record and the postoperative measurement was defined as the accuracy of cup orientation by CT-based navigation according to the definition by Lass [20].

Primary Endpoint

The primary endpoint of this study was to compare the accuracy of acetabular cup inclination and anteversion between the 2D-3D and PPM groups.

Secondary Endpoint

The secondary endpoint of the current study was to investigate the patient-specific factors that affected the accuracy of the cup orientation in CT-based navigation THA.

As patient-specific factors, we assessed body mass index (BMI), pelvic tilt, and absolute value of pelvic tilt on the basis of preoperative planning. APP angle with the patient supine was measured according to a method described by Nisihara [21] during preoperative planning. We used the term pelvic tilt to describe the APP angle in this study. As clinical factors affecting the accuracy of cup orientation, we also assessed Crowe groups, percentages of subluxation defined by Crowe [22], presence of roof osteophytes, and of curtain osteophytes [23] using preoperative plain radiographs. Roof and curtain osteophytes were evaluated by three observers (KY, YF, TM). Existence of an osteophyte was determined only if all observers agreed that it was over 3 mm in length.

Statistical Analysis

Normally-distributed data were analysed using Levine's test for equality of variance. Unpaired Student's t-test was used to compare the patients' demographic data on age, height, body weight, BMI, pelvic tilt, and surgical time, and the accuracy of acetabular cup inclination and anteversion as primary endpoints between 2D-3D and PPM groups. Fisher's exact test was applied to compare sex, treated side, diagnosis, rate of DDH to osteoarthritis, previous pelvic surgeries, presence of roof osteophytes, and that of curtain osteophytes between the groups. The Chi-square test was used to compare Crowe groups and surgical approaches.

We performed subgroup analyses in each group to identify patient-specific factors affecting the accuracy of the cup orientation in CT-based navigation THA. In both groups, objectives were separated into highly-accurate or less-accurate groups in accordance with the average values reported by Kalteis *et al.* (inclination 3.0°, anteversion 3.3°) [15]. Univariate analyses were performed to compare BMI, pelvic tilt, absolute value of pelvic tilt, Crowe groups, percentages of subluxation defined by Crowe, presence of roof osteophytes, and presence of curtain osteophytes between the highly-accurate and less-accurate groups. Multiple logistic regression analyses were then conducted using the accuracy of cup orientation as the objective variable and factors that showed significant differences in univariate analyses as explanatory variables.

We carried out statistical analysis using the Statistical Package for the Social Sciences (SPSS), version 20.0 (SPSS Inc.). Values of $P < 0.05$ were considered statistically significant.

The data of the first 20 hips (10 hips in each group) were used to determine the sample size. The mean accuracy of cup inclination was 2.7° in the 2D/3D group and 4.4° in the PPM group. The standard deviation of the accuracy of cup inclination in these 20 hips was 2.6°. Moreover, the mean accuracy of cup anteversion was 3.2° in the 2D/3D group and 5.1° in the PPM group. The standard deviation of the accuracy of cup anteversion in these 20 hips was 2.7°. The sample size calculation to compare the mean accuracy of cup inclination and anteversion between the two groups was performed by SPSS using the above-mentioned data and the standard assumption ($\alpha = 0.05$, power = 0.8). As a result, the sample size was set to 37 hips for inclination and 32 hips for anteversion in each group. Taking into consideration the possibility of dropouts, the sample size was set at 40 hips in each group in the current study.

Results

Among patients' demographic data, there were no significant differences between 2D-3D and PPM groups (Table 1). We found no significant differences in surgical time between the two groups (Table 1). Navigation systems operated without any problem in all surgeries. None of the patients experienced any postoperative dislocations and none required revision surgery.

The intraoperative record of cup inclination was 42.4° ± 2.3° in the 2D-3D group and 41.7° ± 4.3° in the PPM group. The intraoperative record of cup anteversion was 16.9° ± 4.8° in the 2D-3D group and 18.4° ± 7.6° in the PPM group. The postoperative measurement of cup inclination was 42.8° ± 3.6° in the 2D-3D group and 43.8° ± 5.8° in the PPM group. The postoperative measurement of cup anteversion was 17.8° ± 5.1° in the 2D-3D group and 17.6° ± 7.7° in the PPM group.

The accuracy of cup inclination and anteversion were significantly better in the 2D-3D group (Table 2).

With regard to subgroup analyses for factors influencing the accuracy of the cup position, in

2D-3D-navigated patients, there were no significant differences for any factors (Tables 3, 4). In PPM-navigated cases, on the basis of univariate analyses, the accuracy of cup inclination was significantly decreased in patients with roof osteophytes (Table 5). Furthermore, the accuracy of cup anteversion was significantly reduced in patients with a large absolute value of pelvic tilt (Table 6). From the result of multiple logistic regression analysis, in CT-based paired-point matched navigation, the presence of roof osteophytes was considered a factor related to inaccuracy of cup inclination (odds ratio 8.27, P = 0.0140) (Table 7), and absolute value of pelvic tilt reduced the accuracy of cup anteversion (odds ratio 1.27, P = 0.0222) (Table 8).

Discussion

Using the navigation systems in THA reduced the rate of dislocation and improved the long-term outcomes of implants [24]. Computer navigation also enabled accurate cup placement for patients with deformed pelvises such as secondary dysplastic osteoarthritis [25]. The usefulness of navigation systems has already been described particularly in Japan [16], where the prevalence of secondary dysplastic osteoarthritis is high [17, 26].

In the current study, the CT-based 2D-3D matched navigation system was more useful than the paired-point matched system because it had greater accuracy of cup orientation and was not affected by patient-specific factors such as pelvic deformity and tilt. To date there are no published reports on the accuracy of cup positioning in CT-based 2D-3D matched navigation. To our knowledge, this study is the first clinical report that describes the accuracy of cup orientation using CT-based 2D-3D matched navigation. In addition, there have been few randomized controlled studies concerning the accuracy of the cup position with CT-based navigation systems. Kalteis *et al*. conducted an RCT involving 90 hips affected by primary osteoarthritis alone in order to compare the accuracy of the cup orientation among three groups; CT-based paired-point matched navigation, imageless navigation, and freehand technique [15]. They concluded that a deviation of 3° ± 2.6° for inclination and 3.3° ± 2.3° for anteversion could be achieved by CT-based paired-point matched navigation, which was significantly more accurate than the deviation using the freehand technique and equivalent to imageless navigation. In the current study, despite a high proportion of secondary dysplastic osteoarthritis, the accuracy of cup positioning using 2D-3D matched navigation was higher than that reported by Kalteis *et al*. [15].

Recently, some studies have reported the usefulness of imageless navigation [9, 10, 15, 20, 27], which avoids the problem of radiation exposure. However, Kalteis *et al.* mentioned that imageless navigation has some disadvantages over CT-based systems in patients with abnormal anatomy such as hip dysplasia or post-traumatic deformities [15]. Tsukada *et al.* also described that the accuracy of imageless navigation decreased in obese patients and in patients with hip dysplasia [28]. We also suggest that CT-based navigation is more useful than imageless systems in Japan because we often treat secondary osteoarthritis of the hips [17, 26].

In the current study, subgroup analyses demonstrated that the accuracy of cup orientation in CT-based paired-point matched navigation was lower for anteversion in patients with greater pelvic tilt and for inclination in patients with roof osteophytes. Some elderly patients have remarkable posterior pelvic tilt with the disappearance of lumber lordosis [29]. For these cases, if the acetabular component was placed at the same anteversion as patients with lesser posterior pelvic tilt, the risk of anterior dislocation might increase because the cup anteversion was too large for them [30]. During preoperative planning, we usually set the acetabular cup inclination to 40 degrees. We also normally set the cup anteversion to 20 degrees, which is increased or decreased in accordance with the pelvic tilt and stem antetorsion. With regard to pelvic tilt, we confirmed excessive pelvic posterior tilt on the radiographs with the patients supine and in a standing position for all cases preoperatively. Cup anteversion was then reduced depending on the degree of pelvic posterior tilt to avoid anterior dislocation. In particular, cup anteversion was reduced by 5 degrees for every increase of 10 degrees of pelvic posterior tilt. For example, if the pelvic posterior tilt was less than 10 degrees, the cup anteversion was reduced to 15–20 degrees, and if the pelvic posterior tilt was more than 30 degrees, the cup anteversion was reduced to 0–5 degrees. After cup anteversion was determined, on the basis of combined anteversion theory [31], the stem anteversion was changed to achieve an ideal angle of 37.3 degrees (= cup anteversion + stem antetorsion × 0.7). We occasionally used cemented stems to adjust the stem antetorsion.

Furthermore, osteophyte formation is often identified in the majority of DDH cases at the end stage of coxarthrosis due to the biological reaction [23, 32]. Inaccurate cup inclination in such patients could increase the risk of postoperative dislocation [2] and accelerated polyethylene wear [3]. On the other hand, the accuracy of cup position in 2D-3D matched navigation was not affected by patient-specific factors such as pelvic morphology. The reason for the high accuracy of 2D-3D matched navigation might be that intraoperative two-directional fluoroscopic images of a wide area including bilateral obturator foramens were well matched to the three-dimensional pelvic images reconstructed from preoperative CT data. CT-based 2D-3D matched navigation has not only the great accuracy of the cup orientation but also has advantages for severely deformed hips.

However, CT-based 2D-3D matched navigation has some disadvantages. First, intraoperative loosening of Schantz screws connecting the reference array might lead to an error, as is the case with other navigation systems. In such a situation, surgeons might be unable to continue use of the navigation system. During computer-navigated surgery, we always ensure the difference between the operative view and the navigation screen by direct palpation of the bony landmarks with the pointer. Fortunately, no screw loosening occurred in this study. Second, this system requires preoperative CT images and intraoperative fluoroscopic images, which causes increased costs and raises the issue of radiation exposure [12]. In patients who have near-normal pelvic morphology such as those with primary osteoarthritis or osteonecrosis, we consider that they don't always need CT-based navigation, and imageless navigation is also available to reduce radiation exposure.

This study has at least five limitations. First, three surgeons undertook the surgery in this study. Although the number of surgeries performed by individual surgeons did not significantly differ between the groups, there could be inter-surgeon error in the intraoperative registration. Second, we used three types of surgical approaches. We did not standardize the type of surgical approach used because it has previously been reported that the accuracy of CT-based navigation does not depend on the surgical approach [18]. Moreover, we found no significant difference between the two groups using either surgical approach (Table 1). However, it would be desirable for us to compare the accuracy of navigation systems using only one approach in order to make this study a more standardized one. Third, in the current study, we included seven patients who had previously undergone pelvic surgery (Table 1). Exclusion of these variable cases might be necessary in order to carry out a more high-quality study. However, it was reported in one study that in Japan the prevalence of DDH among patients with osteoarthritis of the hip joint was 81% [26]. As a consequence, in Japan, many THAs have to be performed in patients with severely deformed pelvises or who have previously undergone pelvic osteotomies. We therefore added these anatomically-variable cases to the patient population in this study because in such cases highly accurate navigation systems are required. Fourth, our measurement method for postoperative cup position might be inferior to the volume registration technique used by Iwana *et al*. [16, 33, 34] because our measurement method might be susceptible to error in identifying the APP because our technique could not match the position of the pelvis on pre- and postoperative CT images. On the other hand, the volume registration technique used by Iwana *et al*. is an ideal tool to match the position of the pelvis on pre- and postoperative CT images. However, the technique has not become widespread because other investigators cannot use the technique with their own software. Consequently, we used familiar software to evaluate the cup positioning, as has been done in other studies [8, 9, 14, 15]. Finally, in the current study, we were not able to assess the patient-based outcomes. We believe that there might be no statistically-significant difference between the two groups in terms of short-term clinical results because none of the cases experienced any postoperative dislocations during the study period. However, the 2D/3D method might produce better long-term clinical results such as dislocation rate and polyethylene wear than the paired-point method. Sugano *et al.* reported that CT-based navigation improved the long-term survival in instances of ceramic-on-ceramic THA [24], but it is still unknown whether or not differences between registration methods are clinically significant over the long term. In future, long-term clinical results including patient-based outcomes are required.

Conclusion

In this prospective randomized controlled study, 80 hips including 44 with secondary dysplastic osteoarthritis were divided into a CT-based 2D-3D matched navigation group and a paired-point matched navigation group, and THA was performed. The accuracy of cup orientation was compared between groups using postoperative CT evaluation. Multiple logistic regression analysis was also performed to clarify the patient-specific factors affecting the accuracy of cup position in each navigation system. The accuracy of acetabular component inclination and anteversion in CT-based 2D-3D matched navigation was better than that in paired-point matched navigation. Furthermore, the accuracy of cup position in paired-point matched navigation was negatively influenced by the presence of roof osteophytes and the absolute value of pelvic tilt. On the other hand, the accuracy of cup orientation in 2D-3D matched navigation was not affected by patient-specific factors. CT-based 2D-3D matched navigation proved to be a useful system for performing THA in cases of secondary osteoarthritis with severe deformity.

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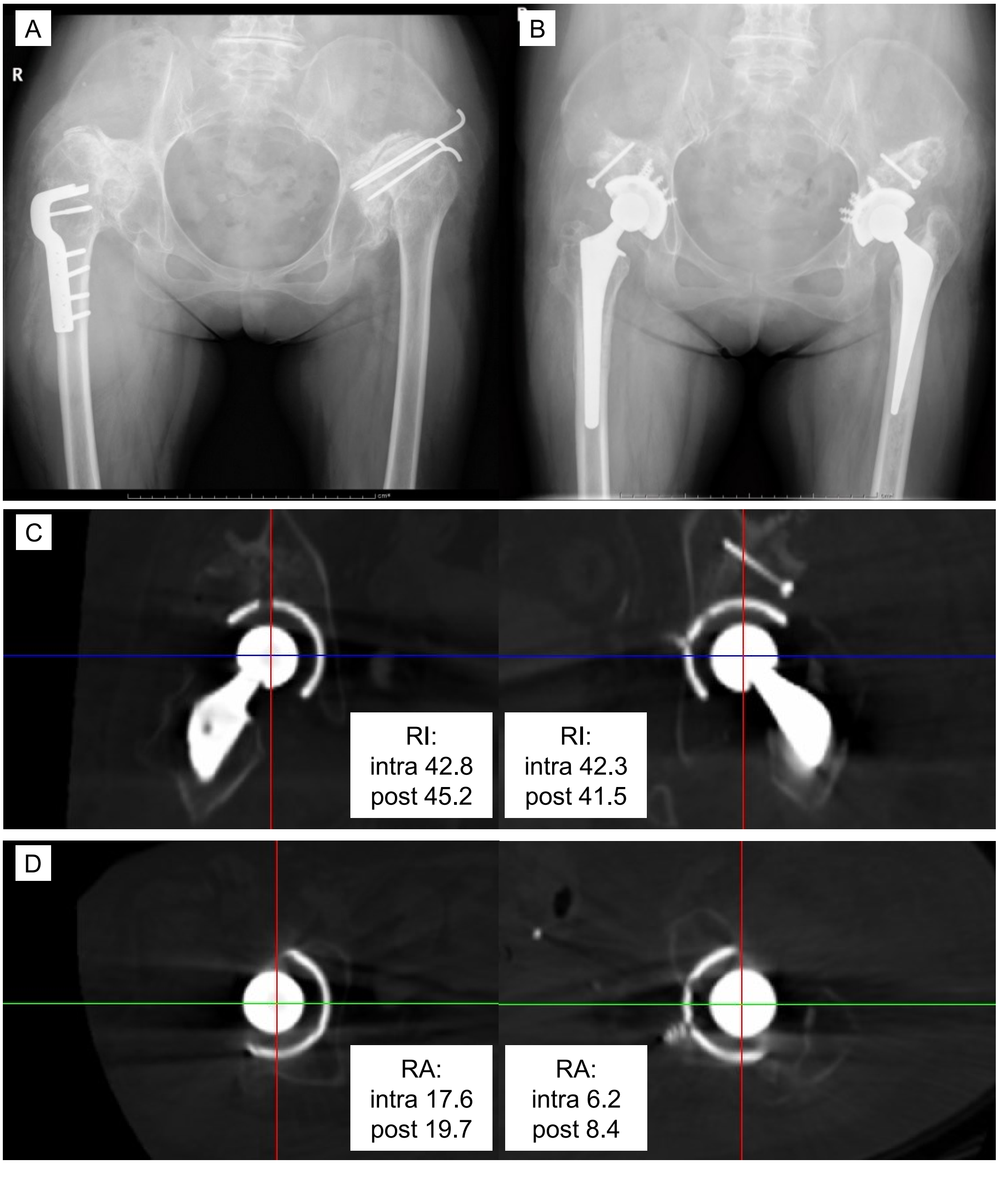

Fig. 1. (A) 57 years-old female with bilateral acetabular dysplasia. She had previously received right femoral valgus osteotomy and left hip arthrodesis. (B) We performed bilateral THA using CT-based 2D-3D matched navigation. (C) (D) Postoperative CT measurement of cup position. Radiographic inclination (RI), radiograhic anteversion (RA), intraoperative record (intra), and postoperative measurement (post) are shown. There is little difference between intraoperative record and postoperative measurement.

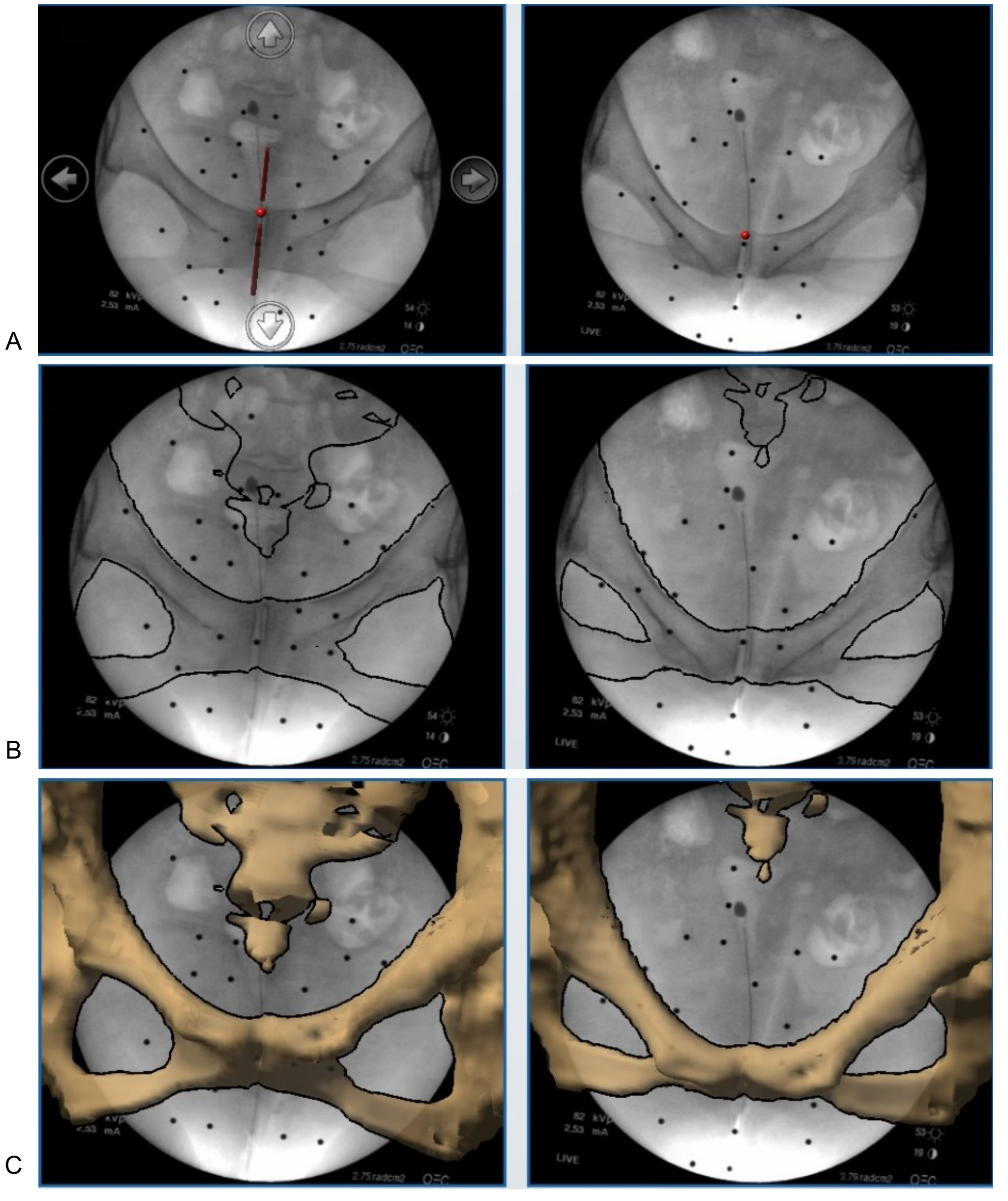

Fig. 2. Intraoperative screenshot of CT-based 2D-3D matched navigation system. (A) Two fluoroscopic pelvic images taken from different angles of more than 20° . (B) (C) Fluoroscopic images were matched to three-dimensional pelvic images reconstructed from preoperative CT data.

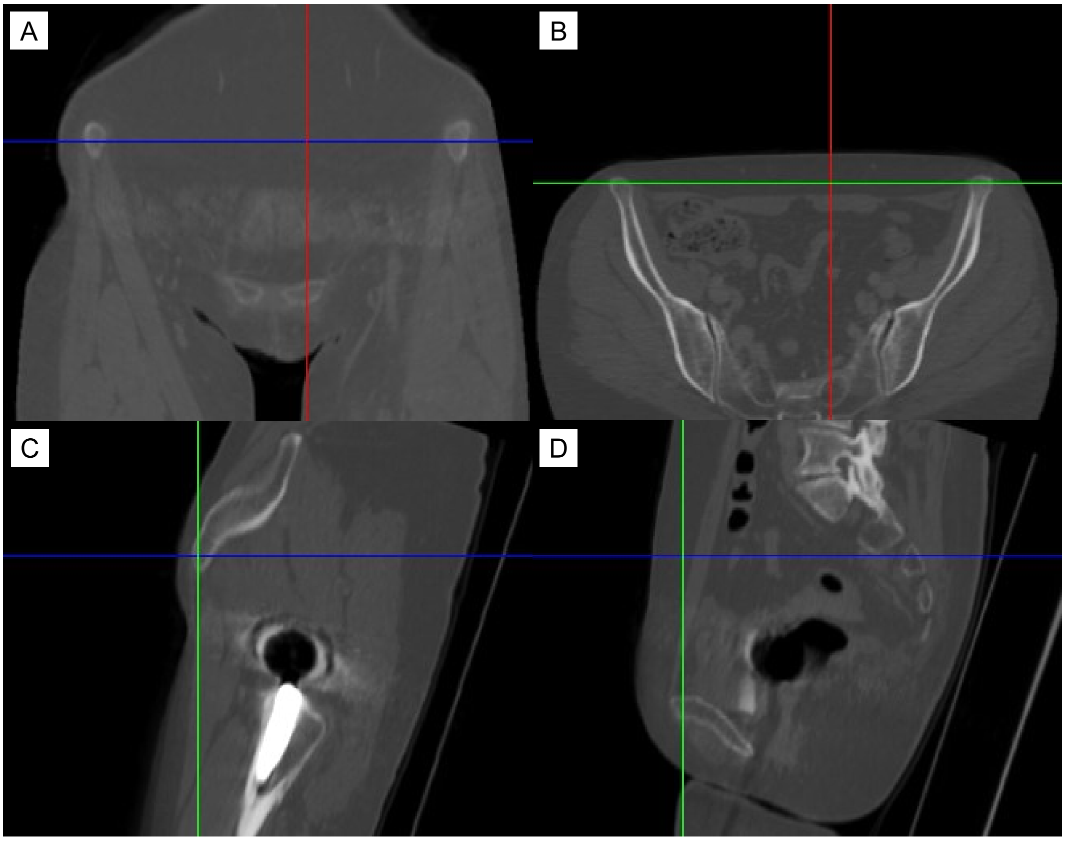

Fig. 3. (A) Pelvic coordinate system, set to the anterior pelvic plane (APP) on tomographic coronal plane. (B) Axial plane, (C) (D) Sagittal plane, perpendicular to the APP.

A

B

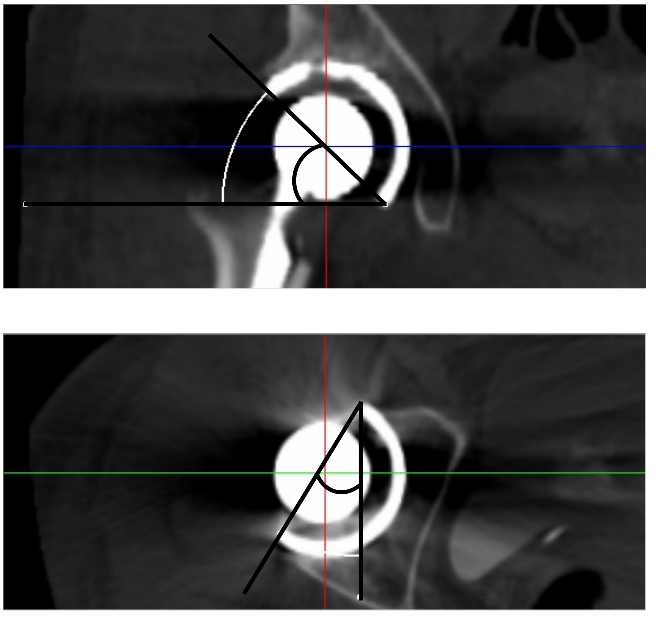

Fig. 4. Measurement of (A) radiographic inclination on the tomographic coronal plane, and (B) anatomical anteversion on the tomographic axial plane.

Table 1
The Patient Demographic Data.

	2D-3D Group (40 hips)	PPM Group (40 hips)	*P* Value
Age (years)	60.8 ± 14.7 (24-84)	63.4 ± 10.5 (41-93)	0.3690[a]
Gender : female/male	29 / 11	36 / 4	0.0834[b]
Treated side : right/left	24 / 16	18 / 22	0.2629[b]
Diagnosis			0.0568[b]
Osteoarthritis	33	39	
DDH	22 / 33 (66.7%)	22 / 39 (56.4%)	0.4736[b]
Osteonecrosis	7	1	
Height (m)	1.56 ± 0.09 (1.36-1.78)	1.52 ± 0.07 (1.37-1.67)	0.0647[a]
Weight (kg)	60.7 ± 15.9 (36.0-108.0)	55.0 ± 10.8 (37.1-85.0)	0.0664[a]
BMI (kg/m^2)	24.4 ± 6.9 (17.7-43.4)	23.7 ± 4.1 (15.8-34.9)	0.5964[a]
Crowe G1/2/3/4	30 / 5 / 2 / 3	28 / 10 / 2 / 0	0.8334[c]
Pelvic tilt (degrees)	2.4 ± 8.4 (-22.1-15.9)	1.3 ± 10.6 (-40.5-15.9)	0.6038[a]
Roof osteophyte	19 (47.5%)	16 (40%)	0.6525[b]
Curtain osteophyte	18 (45%)	21 (52.5%)	0.6549[b]
Surgical approach			0.2345[c]
Posterior	29	25	
Hardinge	8	7	
Modified Watson-Jones	3	8	
Previous pelvic surgery	4 (10%)	3 (7.5%)	1.0000[b]
Rotational acetabular osteotomy	3	0	
Chiari osteotomy	0	1	
Shelf acetabuloplasty	1	0	
Colonna capsular arthroplasty	0	2	
Surgical time (minutes)	133 ± 34.5	125 ± 31.3	0.2574[a]

DDH, developmental dysplasia of the hip.
BMI, body mass index.
Age, Height, Weight, BMI, Pelvic tilt, and Surgical time are expressed as mean ± standard deviation, and range.
[a] Unpaired *t*-test.
[b] Fisher's exact test.
[c] Chi-square test.

Table 2
Absolute Value of Differences in Postoperative Measurement from the Intraoperative Record for the Cup Angle.

	2D-3D Group (40 hips)	PPM Group (40 hips)	*P* Value
Inclination (degrees)	2.5 ± 2.2 (0.1–9.0)	4.6 ± 3.3 (0.2–13.7)	0.0016[a]
Anteversion (degrees)	2.3 ± 1.7 (0.0–8.2)	4.4 ± 3.3 (0.1–14.0)	0.0009[a]

Data are expressed as mean ± standard deviation, and range.
[a] Unpaired *t*-test.

Table 3
Univariate Analysis for the Accuracy of Cup Inclination in CT-Based 2D-3D Matched Navigation System.

	2D-3D Group (40 hips)		
	Inclination ≦ 3° (30 hips)	3° < Inclination (10 hips)	*P* Value
BMI (kg/m^2)	24.9 ± 5.9	24.9 ± 5.1	0.9915[a]
Pelvic tilt (degrees)	4.2 ± 7.0	-2.7 ± 10.5	0.0775[a]
Absolute value of pelvic tilt (degrees)	6.8 ± 4.3	7.9 ± 7.0	0.6386[a]
Crowe G1/2/3/4	23/3/2/2	7/2/0/1	0.7231[c]
Crowe (%)	33.4 ± 32.3	36.7 ± 40.9	0.7963[a]
Roof osteophyte	16 (53.3 %)	3 (30.0 %)	0.2812[b]
Curtain osteophyte	13 (43.3 %)	5 (50.0%)	0.7307[b]

BMI, body mass index.
BMI, Pelvic tilt, Absolute value of pelvic tilt, and Crowe (%) are expressed as mean ± standard deviation.
[a] Unpaired *t*-test.
[b] Fisher's exact test.
[c] Chi-square test.

Table 4
Univariate Analysis for the Accuracy of Cup Anteversion in CT-Based 2D-3D Matched Navigation System.

	2D-3D Group (40 hips)		
	Anteversion ≦ 3.3° (32 hips)	3.3° < Anteversion (8 hips)	*P* Value
BMI (kg/m²)	24.6 ± 4.9	26.2 ± 8.4	0.6260[a]
Pelvic tilt (degrees)	2.8 ± 7.5	0.7 ± 12.4	0.5822[a]
Absolute value of pelvic tilt (degrees)	6.5 ± 4.5	9.7 ± 6.8	0.1369[a]
Crowe G1/2/3/4	23/5/1/3	7/0/1/0	0.3913[c]
Crowe (%)	34.6 ± 36.7	32.6 ± 22.8	0.8854[a]
Roof osteophyte	13 (40.6 %)	6 (75.0 %)	0.1202[b]
Curtain osteophyte	12 (37.5%)	6 (75.0 %)	0.1095[b]

BMI, body mass index.
BMI, Pelvic tilt, Absolute value of pelvic tilt, and Crowe (%) are expressed as mean ± standard deviation.
[a] Unpaired *t*-test.
[b] Fisher's exact test.
[c] Chi-square test.

Table 5
Univariate Analysis for the Accuracy of Cup Inclination in CT-Based Paired Point Matched Navigation System.

	PPM Group (40 hips)		
	Inclination ≦ 3° (15 hips)	3° < Inclination (25 hips)	*P* Value
BMI (kg/m^2)	24.3 ± 4.5	23.4 ± 3.9	0.4799[a]
Pelvic tilt (degrees)	2.2 ± 6.7	0.8 ± 12.5	0.6913[a]
Absolute value of pelvic tilt (degrees)	5.3 ± 4.5	9.2 ± 8.3	0.1019[a]
Crowe G1/2/3/4	8/6/1/0	20/4/1/0	0.0835[c]
Crowe (%)	39.1 ± 27.5	28.0 ± 24.4	0.1919[a]
Roof osteophyte	2 (13.3 %)	14 (56.0 %)	0.0095[b]
Curtain osteophyte	9 (60.0 %)	12 (48.0 %)	0.5266[b]

BMI, body mass index.
BMI, Pelvic tilt, Absolute value of pelvic tilt, and Crowe (%) are expressed as mean ± standard deviation.
[a] Unpaired *t*-test.
[b] Fisher's exact test.
[c] Chi-square test.

Table 6
Univariate Analysis for the Accuracy of Cup Anteversion in CT-Based Paired Point Matched Navigation System.

	PPM Group (40 hips)		
	Anteversion ≦ 3.3° (20 hips)	3.3° < Anteversion (20 hips)	*P* Value
BMI (kg/m²)	24.1 ± 4.3	23.4 ± 4.0	0.5928[a]
Pelvic tilt (degrees)	1.4 ± 7.0	1.2 ± 13.5	0.9429[a]
Absolute value of pelvic tilt (degrees)	5.5 ± 4.4	10.0 ± 8.8	0.0456[a]
Crowe G1/2/3/4	16/3/1/0	12/7/1/0	0.0969[c]
Crowe (%)	29.5 ± 24.3	34.8 ± 27.6	0.5281[a]
Roof osteophyte	5 (25.0 %)	11 (55.0 %)	0.1053[b]
Curtain osteophyte	8 (40.0 %)	13 (65.0 %)	0.2049[b]

BMI, body mass index.
BMI, Pelvic tilt, Absolute value of pelvic tilt, and Crowe (%) are expressed as mean ± standard deviation.
[a] Unpaired *t*-test.
[b] Fisher's exact test.
[c] Chi-square test.

Table 7
Multiple Logistic Regression Analysis for the Accuracy of Cup Inclination in CT-Based Point Paired Matched Navigation System.

Variable	Partial regression coefficient	Standard error	Odds ratio	95% CI		P Value
				Lower	Upper	
Roof osteophyte	2.1130	0.8598	8.27	1.53	44.61	0.0140

CI, confidence interval.

Table 8
Multiple Logistic Regression Analysis for the Accuracy of Cup Anteversion in CT-Based Point Paired Matched Navigation System.

Variable	Partial regression coefficient	Standard error	Odds ratio	95% CI		*P* Value
				Lower	Upper	
Absolute value of pelvic tilt (degrees)	0.2384	0.1043	1.27	1.03	1.56	0.0222

CI, confidence interval.