Comparison of Three-Dimensional Planning-Assisted and Conventional Acetabular Cup Positioning in Total Hip Arthroplasty

A Randomized Controlled Trial

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Background: Malpositioning of the acetabular cup during total hip arthroplasty increases the risk of dislocation, edge-loading, squeaking, early wear, and loosening. We hypothesized that the use of three-dimensional (3-D) visualization tools to identify the planned cup position relative to the acetabular edge intraoperatively would increase the accuracy of cup orientation. The purpose of this study was to compare 3-D planning-assisted implantation and freehand insertion of the acetabular cup.

Methods: This was a prospective randomized controlled study of two groups of twenty-eight patients each. In the first group, cup positioning was guided by 3-D views of the cup within the acetabulum obtained during 3-D preoperative planning. In the control group, the cup was placed freehand. All of the patients were operated on by the same surgeon, through a minimally invasive direct anterior approach with the patient in the supine position. Cup anteversion and abduction angles were measured on 3-D computed tomography (CT) reconstructions. The main evaluation criterion was the percentage of outliers according to the Lewinnek safe zone.

Results: Operative time did not differ between the two groups. The cup anteversion was more accurate in the 3-D planning group (mean difference from the planned angle [and standard deviation], \(-2.7^\circ \pm 5.4^\circ\)) compared with the freehand-placement group (6.6\(^\circ\) ± 9.5\(^\circ\)). According to the Lewinnek safe zone, overall, the percentage of outliers was lower in the 3-D planning group (21%; six patients) than in the control group (46%; thirteen patients). According to the Callanan safe zone, the percentage of outliers was also lower in the 3-D planning group (25% versus 64%). Although cup abduction was also restored with greater accuracy in the 3-D planning group, on the basis of the Lewinnek safe zone, the percentage of abduction outliers was comparable between groups, with fewer high-abduction values, but more low-abduction values, in the 3-D planning group.

Conclusions: Preoperative 3-D planning increased the accuracy of anteversion restoration and reduced the percentage of outliers without increasing the operative time. In this study, the same advantage could not be demonstrated for abduction.

Level of Evidence: Therapeutic Level I. See Instructions for Authors for a complete description of levels of evidence.

A cetabular cup malpositioning during total hip arthroplasty has been associated with several postoperative complications, including dislocation\(^1\)^,\(^2\)^, impingement\(^3\)^, leg-length discrepancy\(^4\)^, edge-loading\(^5\)^, squeaking\(^6\)^, excessive wear\(^7\)^, and higher revision rate\(^8\). Lewinnek et al.\(^9\) recommended an abduction angle within 10\(^\circ\) of 40\(^\circ\) (30\(^\circ\) to 50\(^\circ\)) and an anteversion...
angle within 10° of 15° (5° to 25°) as the safe zone for cup orientation in total hip arthroplasty. Recently, Callanan et al. described a modified safe zone (abduction, 30° to 45°; anteversion, 5° to 25°) in order to take into account the use of hard-on-hard bearing surfaces.

Conventional freehand insertion remains the most widely used technique for cup implantation. To improve the accuracy and reproducibility of the actual three-dimensional (3-D) cup positioning, several techniques have been described, including the use of anatomic landmarks, image-assisted navigation, imageless navigation, and robotic-assisted navigation. These techniques have been demonstrated to improve the accuracy, with lower outlier rates (0% to 25%) compared with conventional insertion (50% to 80%). However, despite their greater accuracy, navigation techniques are not widely used because of the associated extra cost and longer surgical duration.

Recently, 3-D preoperative planning based on computed tomography (CT) imaging showed high accuracy and consistency for hip reconstruction. The authors of that report noted excellent results for femoral stem positioning but lower accuracy for cup anteversion restoration, highlighting the need for guidance systems for cup placement. However, these authors did not use 3-D visualization tools in order to help the surgeon during cup insertion.

We hypothesized that the use of 3-D visualization tools showing the planned cup position relative to the acetabular edge would increase the accuracy of cup orientation compared with that achieved with the conventional freehand implantation method. The goal of this investigation was to compare 3-D planning-assisted positioning with conventional freehand cup placement.

**Materials and Methods**

**Subjects**

From January to December 2009, we performed a prospective randomized controlled study of two groups of twenty-eight consecutive patients each (Fig. 1). The study protocol and consent forms were approved by the local ethical committee. The trial was registered at the ANSM (Agence Nationale de Sécurité du Médicament) registry: BRC identification number 2014-A00921-46.

Patients eligible for inclusion were those undergoing primary total hip arthroplasty performed by the same trained surgeon (E.S.) using a direct anterior approach and with use of a particular cementless press-fit cup (APRIL; Symbios). The exclusion criterion was revision hip surgery. Randomization of patients was done by the clinical research department with use of a systematic sampling method. We used block randomization with a block size of four; within each block, two patients were assigned to procedure 1 (the freehand, or control, group) and two patients were assigned to procedure 2 (the 3-D planning group). All patients provided informed consent to participate in the study.

**Preoperative Planning**

Prior to surgery, patients underwent CT imaging. We then used the images to perform the 3-D planning and surgery simulation to determine the optimal cup size and position. Planning and surgery simulation was performed using the HipPlan (Symbios) software and a low-dose CT scan. A mode combining tube-current modulation and low tube voltage was used to decrease the radiation dose. A postoperative CT scan was also performed, instead of obtaining radiographs usually made at six weeks and three months of follow-up. We followed a low-dose protocol corresponding to 4 mSv, equivalent to that of two
radiographic assessments of the hip (anteroposterior pelvic view and antero-posterior and lateral hip views).

The cup implantation was simulated using 3-D templates with increasing diameters. The 3-D cup template was leveled with the teardrop (the edge of the cortical bone of the cotyloid notch) and placed relative to the medial acetabular wall, which was not crossed, so that the cup was completely covered by the acetabular frame in order to avoid any impingement with soft tissues, such as the psoas tendon. The goals for cup placement were to restore the native acetabular anteversion, avoid the cups exceeding the anterior wall, and achieve a cup abduction of about 40°, as recommended for hard-on-hard total hip arthroplasty.

The cup orientation was mathematically determined using two angles: abduction and anteversion. Because these two values were given, the sagittal cup inclination was automatically fixed. Sometimes the cup may have exceeded the anterior wall on the sagittal view during the 3-D planning. In such a case, the sagittal cup position was modified accordingly. As we maintained the same anteversion value, the cup abduction was consequently modified.

For the freehand group, only the 3-D planned values of the anteversion and abduction angles were given to the surgeon; no guidelines were available regarding the cup orientation. In contrast, for the 3-D planning group, guidelines were given to the surgeon, including a 3-D visualization of the cup within the osseous frame as well as measurements from the cup to the acetabular edge. For the 3-D planning group, image processing was performed in order to remove the femur from the image in order to visualize the acetabulum and the simulated cup position relative to the acetabular bone (Fig. 2-A). Using HipPlan, the distance from the edge of the cup to the edge of the acetabulum was measured relative to the anterior and posterior walls as well as to the superior edge. The postero-caudal overcoverage (noted positively) or undercoverage (noted negatively) of the cup by the posterior wall was measured (Fig. 2-B). The final views of the cup within the acetabular bone were printed and given to the surgeon at the time of surgery.

**Surgical Procedure**

The operation was performed through a minimally invasive, direct anterior approach, with the patient supine on a fracture table. A cementless press-fit hydroxyapatite-coated titanium acetabular component (APRIL), a cementless proximally hydroxyapatite-coated titanium femoral stem (SPS; Symbios), and BIOLOX delta ceramic-on-ceramic bearings surfaces (CeramTec) were used. A standard ancillary was used in the freehand group, including an introducer with an attached version guide. In this group, the cup was positioned according to the surgeon’s assessment based on his experience; no specific system of anatomic landmarks was used.

**TABLE I Demographics and Operative Time**

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Total Hip Arthroplasty Cup Placement Method</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-D Planning-Assisted</td>
<td>Conventional Freehand</td>
</tr>
<tr>
<td>Age* (yr)</td>
<td>60.8 ± 13.4 (55.6 to 66.0)</td>
<td>59.4 ± 10.9 (55.1 to 63.6)</td>
</tr>
<tr>
<td>Sex (no.)</td>
<td>Male 18</td>
<td>Female 10</td>
</tr>
<tr>
<td></td>
<td>Male 20</td>
<td>Female 8</td>
</tr>
<tr>
<td>Side (no.)</td>
<td>Right 17</td>
<td>Left 11</td>
</tr>
<tr>
<td></td>
<td>Right 14</td>
<td>Left 14</td>
</tr>
<tr>
<td>BMI* (kg/m²)</td>
<td>26.6 ± 4.0 (25.0 to 28.3)</td>
<td>26.7 ± 4.3 (25.0 to 28.4)</td>
</tr>
<tr>
<td></td>
<td>26.7 ± 4.3 (25.0 to 28.4)</td>
<td></td>
</tr>
<tr>
<td>Operative time* (min)</td>
<td>88.9 ± 14.8 (82.0 to 95.6)</td>
<td>94.0 ± 23.2 (83.9 to 104.0)</td>
</tr>
</tbody>
</table>

*The values are presented as the mean and the standard deviation, with the 95% confidence interval in parentheses. BMI = body mass index.
In the 3-D planning group, once the cup was inserted, the orientation was modified according to the 3-D images showing its relative position to the acetabular edge. The surgeon used a flexible ruler to measure the distance values of the cup to the acetabular edge, and he compared them with the values determined during the 3-D planning. For this purpose, the surgeon had to visually compare the actual acetabular anatomy with the 3-D views achieved with the HipPlan software in order to find on the acetabular rim the same points as those used in measuring the distance to the cup in the planning: one on the anterior wall, one on the posterior wall, and one on the roof. The design of the cup includes six holes on its periphery. If needed, a smooth impactor (a punch) was introduced in these peripheral holes in order to modify the cup anteversion or the inclination using a hammer (Fig. 3-A). Once agreement between the 3-D planning view (Fig. 3-B) and the surgical view (Fig. 3-C) was achieved, the cup was finally impacted. The postoperative protocols were the same in the two groups, with full immediate weight-bearing recommended.

| TABLE II Difference Between Planned and Final Cup Anteversion and Abduction Angles |
|-----------------------------------------------|-----------------|-----------------|-------|
| Total Hip Arthroplasty Cup Placement Method   | 3-D Planning-Assisted* | Conventional Freehand* | P Value |
| Anteversion (deg)                             | Planned          | 15.4 ± 4.4 (13.7 to 17.2) | 17.7 ± 4.9 (15.6 to 19.8) | 0.12 |
|                                              | Final            | 12.6 ± 6.2 (10.2 to 15)   | 24.8 ± 6.9 (22.1 to 27.5) | 0.001† |
|                                              | Difference       | −2.7 ± 5.4 (−4.8 to −0.5) | 6.6 ± 9.5 (2.6 to 10.6)   | 0.0008† |
| Abduction (deg)                              | Planned          | 39.2 ± 1.5 (38.6 to 39.7) | 40.0 ± 2.7 (39 to 41)     | 0.13 |
|                                              | Final            | 37.6 ± 6.1 (35.3 to 40)   | 43.8 ± 7.7 (40.8 to 46.8) | 0.009† |
|                                              | Difference       | −2.0 ± 6.5 (−4.4 to 0.5)  | 3.9 ± 7.5 (1 to 6.7)      | 0.003† |

*The values are presented as the mean and the standard deviation, with the 95% confidence interval in parentheses. A negative value is shown if the mean final value was lower than the mean planned value. Greater accuracy was found in the 3-D planning group compared with the conventional freehand-placement group. †Significant.

In the 3-D planning group, once the cup was inserted, the orientation was modified according to the 3-D images showing its relative position to the acetabular edge. The surgeon used a flexible ruler to measure the distance values of the cup to the acetabular edge, and he compared them with the values determined during the 3-D planning. For this purpose, the surgeon had to visually compare the actual acetabular anatomy with the 3-D views achieved with the HipPlan software in order to find on the acetabular rim the same points as those used in measuring the distance to the cup in the planning: one on the anterior wall, one on the posterior wall, and one on the roof. The design of the cup includes six holes on its periphery. If needed, a smooth impactor (a punch) was introduced in these peripheral holes in order to modify the cup anteversion or the inclination using a hammer (Fig. 3-A). Once agreement between the 3-D planning view (Fig. 3-B) and the surgical view (Fig. 3-C) was achieved, the cup was finally impacted. The postoperative protocols were the same in the two groups, with full immediate weight-bearing recommended.

Fig. 3
At the time of surgery, the cup was oriented using a punch impactor (Fig. 3-A) until the planned position (Fig. 3-B) and the final position (Fig. 3-C) matched. The dot corresponds to the distal part of the cotyloid notch. In Figure 3-A, the dashed line indicates the acetabular frame, and the arrows indicate the anterocaudal and the posterocaudal coverage of the cup by the acetabular bone. In Figures 3-B and 3-C, the dashed line indicates the vertical orientation, and the arrows correspond to the distance from the cup to the posterocaudal acetabular edge.
Postoperative Evaluation
In order to compare the planned cup position with the final position, a matching of the preoperative and the postoperative CT scans was performed with the HipPlan software by aligning the pelvic bone landmarks (Fig. 4). The radiographic cup anteversion and abduction angles were measured in the anterior pelvic plane on 3-D CT reconstructions for each patient by an independent observer. Excellent agreement was previously reported for the reproducibility of these angular measurements using the HipPlan software.

Evaluation Criteria
The main evaluation criterion was the percentage of outliers according to the Lewinnek safe zone. The secondary evaluation criteria were the percentage of outliers according to the Callanan safe zone and the mean difference between the postoperative and the planned cup orientation angles (anteversion and abduction). The assessments were performed by E.S., who was blinded as to which group the patient was assigned.

Statistical Analysis
On the basis of the literature, the sample size calculated to provide a power ($1 - \beta$) of 0.80 and a type-I error rate ($\alpha$) of 0.05 was twenty patients per group with an expected percentage of outliers of 65% in the freehand group and 17% in the 3-D planning group.

We first analyzed the accuracy of both methods through a two-group pair comparison of the planned and postoperative acetabular anteversion and abduction angles. Means and variances of the cup position achieved with the 3-D planning technique were compared with those achieved with the freehand method.
method. The accuracy of the restoration of the angles was expressed as the mean difference and standard deviation of the planned position compared with the final position. The Pearson coefficient ($r$) was used to assess the correlation between planned and postoperative cup anteversion and abduction. Then we determined, within each group, the percentage of cups outside the safe zone (outliers) as described by Lewinnek et al. and also by Callanan et al. The percentages of outliers were compared between groups using a chi-square test. Statistical analysis was performed with JMP software (version 11; SAS Institute) as a two-group pair comparison with a t test for a comparison of the means. A $p$ value of $<0.05$ was considered significant.

**Source of Funding**

No external funding was received for this study.

**Results**

Demographic data did not differ significantly between the two groups (Table I). The mean age of the patients (and standard deviation) was $59.4 \pm 10.9$ years (range, twenty-six to seventy-six years) in the freehand group and $60.8 \pm 13.4$ years (range, twenty-three to eighty-three years) in the 3-D planning group. The etiology requiring total hip arthroplasty was primary osteoarthritis in twenty-two hips and osteonecrosis in six hips in the freehand group, and primary osteoarthritis in twenty-three hips and osteonecrosis in five hips in the 3-D planning group. The mean diameter of the acetabular cup was $52$ mm in both groups. There was no significant difference in operative time between the two groups ($p = 0.2$). In the 3-D planning group, the restoration of the native acetabular anteversion corresponded to a posterocaudal overcoverage of the cup by the posterior horn of $12 \pm 4$ mm (Fig. 3). No patient had a neurovascular complication, and no dislocation occurred in the four years after surgery.

**Fig. 5**

There was a significant correlation (*) between the planned and the final postoperative values of cup anteversion in the 3-D planning group (Fig. 5-A), but there was no correlation between these two values in the freehand group (Fig. 5-B).

**Fig. 6**

The difference between the planned and the final cup anteversion angles is demonstrated. The boxes indicate the 25th and 75th percentiles.
In the 3-D planning group, the mean planned cup anteversion value (15.4° ± 4.4°) did not differ significantly from the postoperative value (12.6° ± 6.2°) \((p = 0.1)\), and a moderate correlation between these two values was found \((r = 0.53; p = 0.004)\) (Fig. 5). In contrast, in the freehand group, there was poor agreement between the planned and postoperative cup anteversion values, with no significant correlation found between the two values \((r = 0.02; p = 0.3)\) (Fig. 5-B). In fact, the mean postoperative cup anteversion value was significantly higher \((24.8° ± 6.9°)\) than the mean planned value \((17.7° ± 4.9°)\) \((p = 0.0004)\). The results are summarized in Tables II and III.

The accuracy of cup anteversion restoration was significantly better in the 3-D planning group \((-2.7° ± 5.4°)\) compared with that in the freehand group \((6.6° ± 9.5°)\) \((p = 0.0008)\). The standard deviation was also significantly lower in the 3-D planning group \((p = 0.0004)\) (Fig. 6).

In the 3-D planning group, no significant difference was found between the mean planned cup abduction value \((39.2° ± 1.5°)\) and the postoperative value \((37.6° ± 6.1°)\) \((p = 0.1)\), and a moderate correlation between these two values was found \((r = 0.45; p ≤ 0.006)\). In contrast, in the freehand group, the mean postoperative cup abduction value was significantly higher \((43.8° ± 7.7°)\) than the mean planned value \((40.0° ± 2.7)\) \((p < 0.009)\), and there was a weak correlation between the planned and postoperative values \((r = 0.2)\). The accuracy of cup abduction restoration was significantly greater in the 3-D planning group \((-2.0° ± 6.5°)\) than in the freehand group \((3.9° ± 7.5°)\) \((p = 0.003)\).

On the basis of the Lewinnek safe zone, the percentage of outliers was lower in the 3-D planning group \((21%; six of twenty-eight)\) than in the freehand group \((46%; thirteen of twenty-eight)\) \((p = 0.04)\). Of the six outliers in the 3-D planning group, four were out of the abduction safe zone, and two were out of both safe zones. Of the thirteen outliers in the freehand group, two were out of the abduction safe zone, and two were out of both safe zones. In the 3-D planning group, three patients were outliers because of low abduction angles, and only one patient had a high abduction angle, whereas in the freehand group, four outliers had an abduction angle of >50°.

On the basis of the Callanan safe zone, the percentage of outliers was also lower in the 3-D planning group \((25%; seven of twenty-eight)\) than in the freehand group \((64%; eighteen of twenty-eight)\) \((p = 0.003)\) (Fig. 7).

**Discussion**

The main finding of this study was that preoperative 3-D planning-assisted cup placement had greater accuracy than did conventional freehand positioning. The native acetabular anteversion was reproduced with a greater accuracy, and there were also smaller standard deviations in the 3-D planning group. The use of the 3-D planning technique significantly reduced the percentage of outliers, from 46% to 21% according to the Lewinnek safe zone and from 64% to 25% according to the Callanan criteria.

However, the 3-D technique had lower accuracy than that reported for CT-based navigation14,15. Recently, Iwana et al.15 reported a difference of 1.8° ± 1.6° for abduction and 1.2° ± 1.1° for anteversion. Furthermore, many studies14-16 have shown 100% of cases within the Lewinnek safe zone when using these technologies. In contrast to CT-based navigation, the 3-D planning-based cup placement did not increase operative time, making this novel technique an attractive option despite its lower accuracy; 3-D planning may be a good compromise between accuracy on the one hand and extra cost and duration of surgery on the other hand. The use of custom patient-specific acetabular alignment guides20 may also improve the accuracy of 3-D planning.

One of the strong points of our study was that the preoperative 3-D anatomy was analyzed and the goal for cup anteversion was known beforehand. Therefore, the accuracy of both techniques was assessed by comparing the final cup anteversion angles with the planned values. Few studies have analyzed the goals...
of cup orientation using preoperative CT scans, and most of the authors used placement within the safe zone as the basis of their evaluation because the preoperative acetabular values were not available, making the calculation of accuracy not feasible.

Another strong point of our study was the use of matching between the preoperative and postoperative CT scans. This technique reduces the risk of error related to pelvic orientation, which may change after total hip arthroplasty by up to 15° in the sagittal plane. This error cannot be well controlled when using conventional radiographs.

On the other hand, the most obvious limitation of this study was that all patients were operated on by the same surgeon. However, Reize et al. reported a prospective study investigating accuracy in cup positioning according to the surgeon’s experience, and they found no significant difference between the high-experience group and the low-experience group. In our future work, we will replicate the present study with a variety of surgeons with different skill levels.

Another limitation of the study was the methodology used to determine, at the time of surgery, the points on the acetabular rim where the measurements to the cup were to be made. This step relied on the surgeon’s judgment, which introduces a risk of error. Assessments of the planning versus the final images were made blinded to group assignment.

There was an equal number of outliers for the abduction angle in both groups; however, in the 3-D planning group, only one patient had a high abduction angle, whereas in the freehand group, all of the outliers were >50°, suggesting that 3-D planning helps to avoid high abduction values that are correlated with an increased risk of edge-loading, excessive wear, ceramic fracture, and squeaking.

The 3-D technique had greater accuracy for anteversion than for restoration of the abduction angle. This may be related to a poor exposure of the proximal part of the acetabulum through the minimally invasive approach, thus preventing the surgeon from accurately measuring the distance from the cup to the superior edge. A cranial extension of the approach should be considered because the minimally invasive direct anterior arthroplasty probably compromised abduction in both groups.

In the 3-D planning group, the restoration of the native acetabular anteversion corresponded to a posterocaudal overcoverage of the cup by the posterior horn of 12 ± 4 mm. This overcoverage gives an impression of cup retroversion, which may explain why, in the freehand group, the final anteversion value was higher than the native anteversion value.

Since the 19th century, it has been recognized that there are problems with making judgments about angles on the basis of human vision alone. We tend to underestimate acute angles such as cup anteversion values, which are typically about 15°. Therefore, when aiming for an angle of 15°, the surgeon will naturally tend to implant the cup with a higher anteversion because the human vision tends to underestimate the final anteversion angle. These findings suggest that human vision is not perfectly reliable when trying to restore angles, highlighting the value of guidance systems such as 3-D planning-based visualization tools.

In conclusion, the use of 3-D preoperative planning can improve cup positioning in total hip arthroplasty by increasing the accuracy of the restoration of anteversion and reducing the percentage of outliers. When using a direct anterior approach with the patient in the supine position, the surgeon intuitively tends to implant the cup with a higher anteversion value than that of the native acetabulum anteversion because of the posterocaudal overcoverage of the cup that gives a false impression of cup retroversion. We do not have evidence that achieving our preoperative planned cup position has any effect on clinical outcome.

References


