Digital Radiography in Total Hip Arthroplasty

Technique and Radiographic Results

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Background: Obtaining the ideal acetabular cup position in total hip arthroplasty remains a challenge. Advancements in digital radiography and image analysis software allow the assessment of the cup position during the surgical procedure. This study describes a validated technique for evaluating cup position during total hip arthroplasty using digital radiography.

Methods: Three hundred and sixty-nine consecutive patients undergoing total hip arthroplasty were prospectively enrolled. Preoperative supine anteroposterior pelvic radiographs were made. Intraoperative anteroposterior pelvic radiographs were made with the patient in the lateral decubitus position. Radiographic beam angle adjustments and operative table adjustments were made to approximate rotation and tilt of the preoperative radiograph. The target for cup position was 30° to 50° abduction and 15° to 35° anteversion. Intraoperative radiographic measurements were calculated and final cup position was determined after strict impingement and range-of-motion testing. Postoperative anteroposterior pelvic radiographs were made. Two independent observers remeasured all abduction and anteversion angles.

Results: Of the cups, 97.8% were placed within 30° to 50° of abduction, with a mean angle (and standard deviation) of 39.5° ± 4.6°. The 2.2% of cups placed outside the target zone were placed so purposefully on the basis of intraoperative range-of-motion testing and patient factors, and 97.6% of cups were placed between 15° and 35° of anteversion, with a mean angle of 26.6° ± 4.7°. Twenty-eight percent of cups were repositioned on the basis of intraoperative measurements. Subluxation during range-of-motion testing occurred in 3% of hips despite acceptable measurements, necessitating cup repositioning. There was 1 early anterior dislocation.

Conclusions: Placing the acetabular component within a target range is a critical component to minimizing dislocation and polyethylene wear in total hip arthroplasty. Using digital radiography, we positioned the acetabular component in our desired target zone in 97.8% of cases and outside the target zone, purposefully, in 2.2% of cases. When used in conjunction with strict impingement testing, digital radiography allows for predictable cup placement in total hip arthroplasty.

Improper acetabular component position during total hip arthroplasty is a major factor associated with dislocation due to impingement and early failure due to polyethylene wear[1-4]. These modes of failure contribute to 25% of revision total hip arthroplasties. Femoral-neck impingement, decreased range of motion, limb-length discrepancies, and gait disturbances have all been associated with incorrect acetabular cup positioning[1-13]. Notably, the cost of each total hip arthroplasty revision is >150% of the cost of a primary total hip arthroplasty[14,15].

In 1978, Lewinnek et al. defined a safe zone of 30° to 50° cup abduction and 5° to 25° anteversion, which, in his series, was associated with a reduced rate of dislocation[2]. Others have recommended an abduction angle of 40° to 45° or 30° to 55° to preserve stability and to prolong implant survivorship[8,11,13,14,16-22]. In a more recent study, Abdel et al. suggested that hip stability is likely multifactorial and acetabular cup position is merely one important factor in achieving successful outcomes with total hip arthroplasty[23]. Impingement and range-of-motion testing intraoperatively in addition to obtaining a target acetabular position can together help to minimize total hip arthroplasty dislocations.

In spite of this understanding, there is biomechanical evidence that placement of the cup within a target range decreases polyethylene wear and instability[1-4]. Because of the importance of achieving correct acetabular cup position, new technology in the form of robotic or computed tomography

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Fig. 1

Photograph showing the setup for an intraoperative anteroposterior pelvic radiograph with the patient in the lateral decubitus position. A cordless cassette is placed posterior to the sterile field. A standard portable x-ray machine is positioned anteriorly. A sterile drape can easily be placed over the cassette.

(CT)-based guidance systems has been developed, all aimed to obtain appropriate acetabular cup position as measured on the postoperative radiograph. These advancements stem from literature-reported rates of acetabular component placement in a target range of 30° to 45° in only 62% of cases and in the range of 30° to 50° in up to 85%[24-27]. Typical alignment guides are limited in that they are spatially oriented with reference to the operating room or an assumed pelvic position. Movement of the patient introduces errors leading to inaccuracy[28]. Although CT-based computer navigation systems and robotic-guided systems have been reported to yield improved cup positioning[17,18,21,22,27,29-40], the high cost, additional preoperative imaging, added radiation exposure, time for setup in the operating room, and difficulty with obese patients have limited the widespread use of these techniques. A 2014 study used intraoperative fluoroscopy during total hip arthroplasty and showed improvement in cup positioning compared with conventional techniques[41].

Given these challenges, digital radiography appears to have the potential to offer a more definitive solution for achieving and confirming precise cup position during total hip arthroplasty[42]. It would make the gold-standard measurement available to the surgeon in the operating room with the patient in the lateral decubitus position. The purpose of this study was to report on the reliability of intraoperative digital imaging in predicting postoperative cup abduction and anteversion in total hip arthroplasty.

Materials and Methods

Study Cohort

Three hundred and sixty-nine consecutive primary total hip arthroplasty cases performed between August 2012 and April 2014 were included in this study. Institutional review board approval was obtained. No patients were excluded. There were 210 right total hip arthroplasties (56.9%) and 159 left total hip arthroplasties (43.1%). Forty-one patients (11.1%) had previously undergone contralateral total hip arthroplasty. Osteoarthritis of the hip was present in 94% of patients, femoral-head osteonecrosis was present in 4% of patients, and developmental dysplasia or rheumatoid arthritis was present in the remaining 2% of patients. The mean operative time was 85 minutes (range, 40 minutes to 2.5 hours). There were 45% male patients and 55% female patients. The mean body mass index (BMI) was 27.5 kg/m^2 (range, 17 to 44 kg/m^2), with 32% of patients having a BMI of >30 kg/m^2.

Preoperative Visit

All patients had digital preoperative supine anteroposterior pelvic radiographs with the lower extremities in 15° to 20° of internal rotation and natural pelvic tilt with the beam perpendicular to the table at a distance of 40 inches (1 m) from the patient and centered over the pubic symphysis. This served as the reference radiograph for intraoperative radiographs.

Surgical Steps

A senior arthroplasty surgeon performed all total hip arthroplasties using a soft-tissue-sparing posterior approach with patients in the lateral decubitus position[29]. Ninety-six percent were secured using a peg-board with radiolucent pegs, and 4%, with an extraordinarily protuberant abdomen, were secured using the OSI device (Mizuho Orthopedic Systemic) with a curved arm and small, rounded pads on the symphysis. Traditional techniques were used for cup and screw placement, femoral broaching, and limb-length and offset assessment. We used the distance from the interteardrop line to the lesser trochanter to determine limb length. The actual cup, not a trial, was positioned using standard alignment guides along with observation of the cup relationship to the anterior and lateral acetabular rim. No screws or only 1 screw, depending on quality of bone, is the surgeon's preferred technique. Digital radiography confirmed acceptable screw position. A trial liner was utilized, anticipating the possibility of cup or screw adjustment. The best-guess femoral broach placement was completed on the basis of preoperative templating. Neck and head choices were made on the basis of estimates of limb length and offset. Trial range of motion was then carried out.

The first trial radiograph was then made using a standard portable x-ray unit, a digital flat panel detector, and a portable digital radiography processing system (Radlink). Initial radiographs were always used with the actual cup. All radiographs were made with the center of the beam directed to the pubic symphysis (Fig. 1).

Obtaining neutral pelvic rotation and matching pelvic tilt to preoperative radiographs during intraoperative imaging is critical to obtaining accurate intraoperative measurements. The pelvis was considered to be in neutral axial rotation if a vertical line passing through the pubic symphysis, perpendicular to an interteardrop line, bisected the sacrum. If a match was not achieved on the first radiograph, radiographs were repeated as necessary after moving the operating table or radiographic unit. In some cases, pelvic tilt approximated, but was not identical to, the preoperative

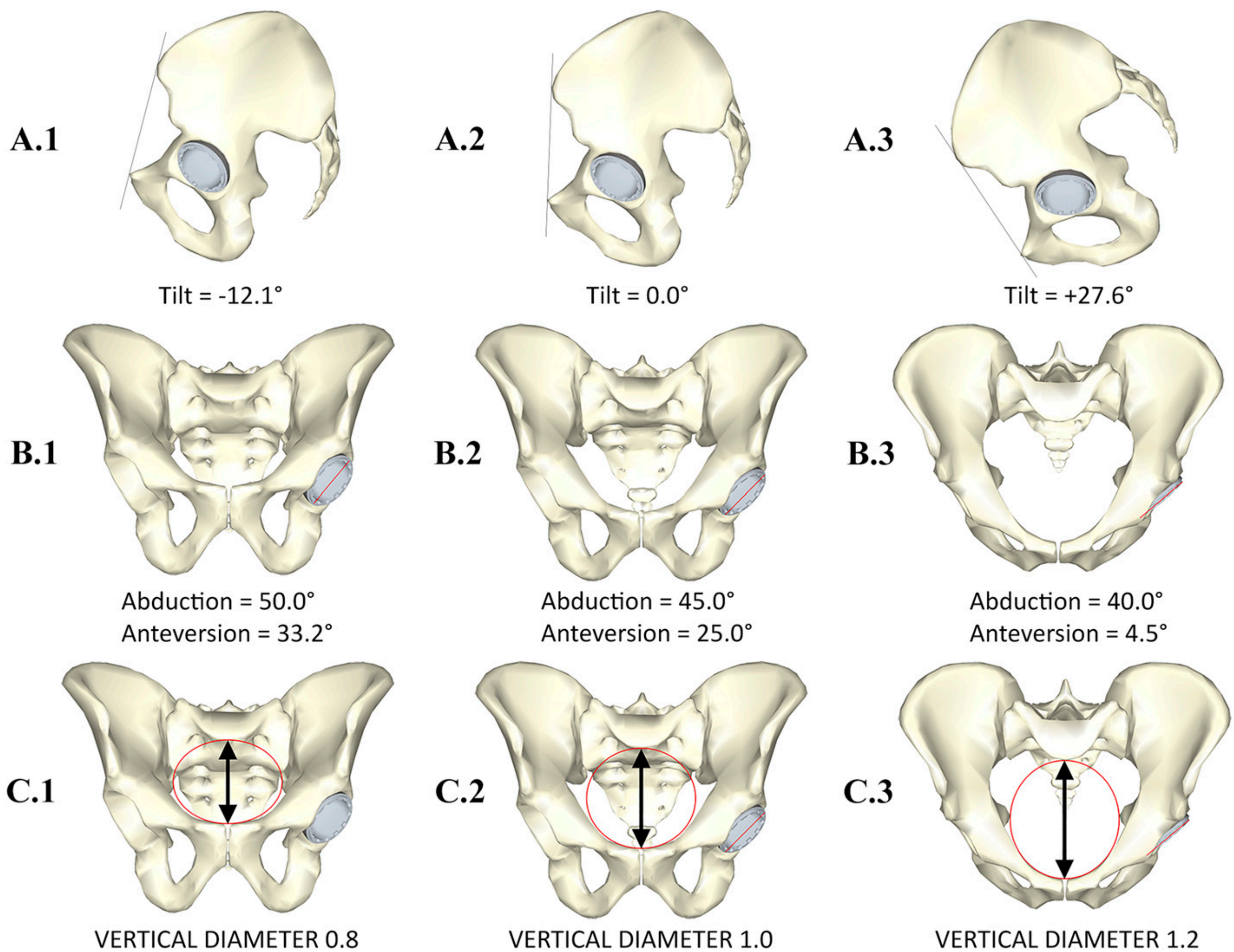

Fig. 2

This illustration represents a model that identifies a series of predictable changes in abduction angle as pelvic tilt changes. In this example, tilting the pelvis forward (A.3) from a neutral position (A.2) decreases the abduction and anteversion angles (B.3). Tilting the pelvis back (A.1) increases the abduction and anteversion angles (B.1). A change in the vertical diameter of 20% produces approximately 5° of change in cup abduction angle (C.1-C.3). These observations have served as a general guideline in making intraoperative estimates when the reference radiograph is different from the intraoperative radiograph. The accuracy of these predictions may vary on the basis of the exact dimensions of the pelvis.

radiograph. In these cases, modifications were made in measurement predictions based on observations seen in Figure 2.

Intraoperative Measurement Techniques

The surgeon remained scrubbed and performed all radiographic measurements on a touchscreen using a Kocher clamp to activate imaging analysis software. Gloves were then changed. The following parameters were measured: acetabular cup angle, cup anteversion, pelvic tilt and rotation, limb-length assessment, femoral offset, and canal fit and orientation. In this study, we limit our data analysis to acetabular component abduction angle and anteversion. Teardrops were identified and the transpelvic reference axis was drawn. The abduction angle measurement was performed with 1 arm along the edge of the cup and the other along the interteardrop line[2,31] (Fig. 3). Anteversion was measured by drawing 2 perpendicular lines from edge to edge across the major and minor diameters of the cup[43] (Fig. 3). An example of an unacceptable intraoperative cup abduction angle and an adjusted cup can be seen in Figure 4.

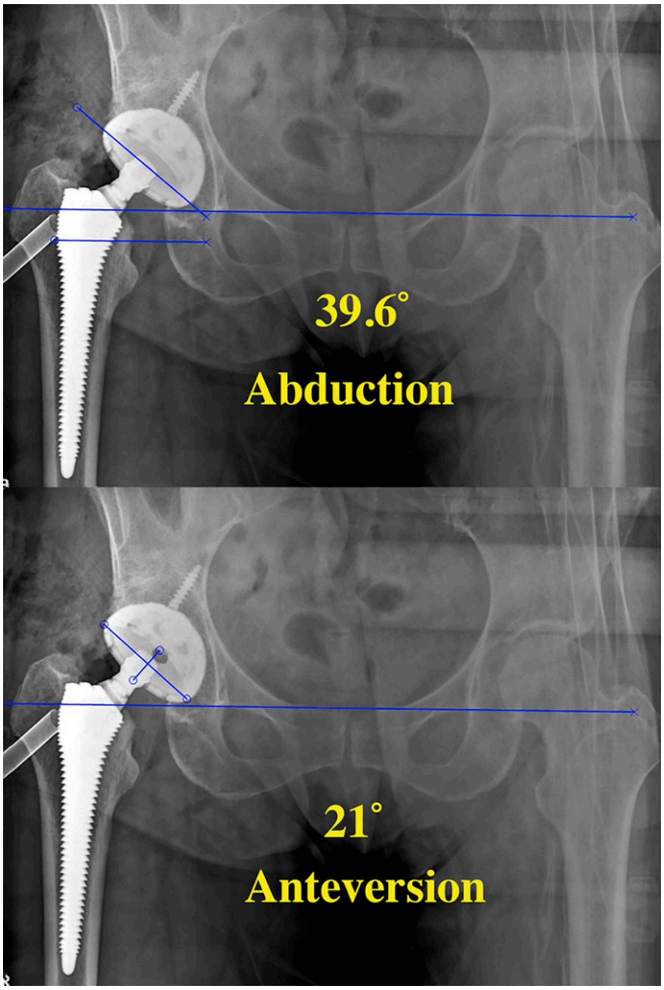

Fig. 3

Example of the technique for intraoperatively measuring cup abduction (top) and cup anteversion (bottom).

The target zone for the cup was 30° to 50° of abduction and 15° and 35° of anteversion. Once the ideal position was confirmed on the radiograph, the hip was again put through a trial range of motion in an effort to identify impingement. Careful intraoperative assessment was conducted at the extremes of motion. The hip was flexed, bringing the thigh to the chest in neutral abduction-adduction and neutral rotation. Mid-flexion stability was tested with combined 60° of flexion, 30° of adduction, and up to 80° of internal rotation. Anterior stability was tested with the combination of maximal hip extension, external rotation, and adduction. If there was impingement or instability (femoral-head subluxation or neck-rim contact posteriorly) after osteophyte removal, acetabular component position was adjusted until stability was achieved, even if it required placing the cup outside of the target zone. Some cups were purposefully left outside of the target zone, especially in more elderly patients with softer bone in whom cup modification could have compromised a press-fit. Final radiographs were made with all implants in place prior to closure. All patients had a standard supine postoperative radiograph made at 2 to 3 weeks postoperatively. A sample series can be found in Figures 5 and 6.

Intraoperative to Postoperative Comparisons

Two independent observers retrospectively analyzed all intraoperative and postoperative radiographs. Abduction and anteversion angles were measured. Observers were blinded to each other's measurements but not to intraoperative or postoperative status. Through analysis of postoperative supine radiographs, the efficacy and accuracy of intraoperative digital radiography could be measured.

To validate the new digital intraoperative imaging software, we also measured cup inclination angles on standard postoperative anteroposterior pelvic radiographs with a previously established method (Martell Hip Analysis Suite; the University of Chicago) and compared those results with results obtained using the Radlink GPS software[19].

Data Analysis

R software was used to perform statistical analysis. Interoperator agreement was assessed by calculating the Pearson correlation coefficient for final intraoperative and postoperative cup abduction angles for observers 1 and 2. A similar analysis was also carried out for observer 1 (using Radlink GPS software) and observer 3 (using the Martell Hip Analysis Suite). A paired 2-tailed t test was carried out for hip abduction angles from the final derived intraoperative and postoperative radiographs.

Results

Of the components, 97.8% were placed within the target zone of abduction (Fig. 7), and 97.6% were placed within 15° to 35° of anteversion. It is important to note

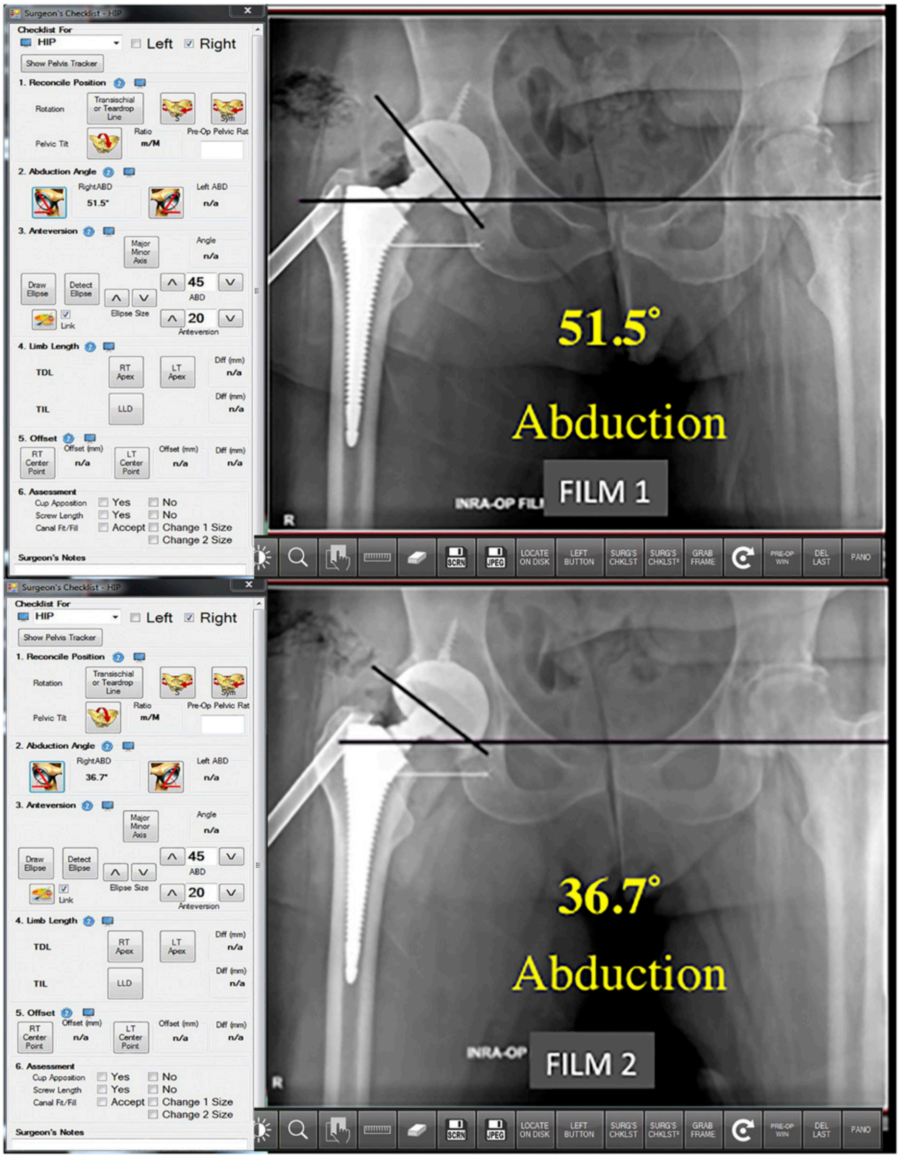

Fig. 4

A trial radiograph with an unacceptable abduction angle (top). The component was then adjusted and the repeated radiograph shows a satisfactory cup position (bottom).

that the 2.2% of patients whose components were outside of the target zone were identified at the time of the surgical procedure. These cups were not repositioned if range-of-motion testing proved absolute stability in the extremes of motion and especially if it was an elderly patient with softer bone, in whom making adjustments to the cup might have compromised primary press-fit fixation. The mean postoperative abduction angle (and standard deviation) was 39.5° ± 4.6° (range, 22° to 51°), and the mean postoperative anteversion angle was 26.6° ± 4.7° (range, 14° to 41°).

A mean of 3 intraoperative digital radiographs (range, 2 to 8 radiographs) were obtained on each hip, equating to a mean radiation exposure of 0.9 mSv (0.3 mSv × 3)[44,45]. The intraoperative radiographs were repeated in 88% of cases in an effort to match the preoperative radiograph. In the span of 20 to 30 seconds, the operating room table or the radiographic unit was repositioned to ensure a close approximation of the reference radiograph. Time from radiographic exposure to image display was approximately 4 seconds.

The cup was repositioned in 28% of cases on the basis of the abduction or anteversion measurements. Despite placement of the cup in the target zone, subluxation during range-of-motion testing occurred in 3% of cases. Cup position was adjusted until impingement was eliminated during the trial range of motion.

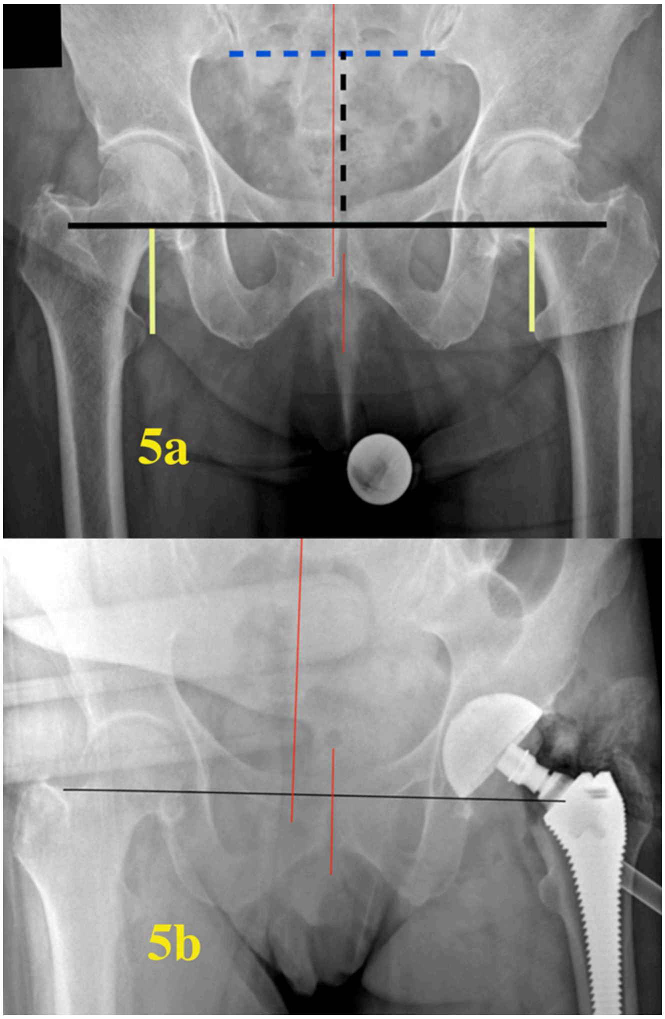

Fig. 5

Sample radiograph series showing preoperative and unacceptable intraoperative radiographs. Pelvic orientation of the intraoperative radiograph ideally will closely match the inlet orientation of the preoperative radiograph. **Fig. 5-A** Preoperative reference radiograph with minimal rotation (mid-sacral line-symphysis offset, <5 mm [red vertical lines]). **Fig. 5-B** Intraoperative, unacceptable, malrotated radiograph. Note the mid-sacral line offset from a line drawn within the symphysis.

When comparing postoperative radiographs with intraoperative radiographs, 93.5% of cases had postoperative abduction angles within 5° of intraoperative measurements and 98.1% had postoperative anteversion angles within 5° of intraoperative measurements. There was excellent interobserver agreement, with a Pearson correlation coefficient between observer 1 and observer 2 of 0.95 for the abduction angles and 0.93 for the anteversion angles. The correlation coefficient between observer 1 and observer 3 (using a previously accepted method, Martell Hip Analysis Suite) was 0.91 on the postoperative radiographs.

At the final follow-up of this cohort at a minimum of 2 years (range, 24 to 40 months), 1 patient sustained an anterior dislocation at 2 months postoperatively in spite of the cup position being in the target zone (42.5° abduction and 25° anteversion). This necessitated a revision surgical procedure and the hip remained stable postoperatively during a further follow-up of 2 years from the time of revision. The dislocation was found to be due to posterior impingement, which was identified through range-of-motion testing at the time of revision. Prior to this case, extension and external rotation alone were used to test for posterior impingement. When adduction was added, posterior impingement and anterior dislocation could be reproduced in this patient. Since this dislocation, the primary surgeon has added adduction when testing for posterior impingement. At the time of this writing, to our knowledge, there have been no further dislocations, with an overall dislocation rate of 0.27% (1 of 369). There were no infections, no reoperations for iliopsoas impingement, no reoperations for limb-length inequality, no other component revisions, and no wound complications or nerve injuries in this cohort.

Discussion

This current study demonstrates a validated technique for accurate acetabular cup positioning during total hip arthroplasty using intraoperative digital radiography. Our results in this 369-patient cohort identified an extremely high level of accuracy for cup positioning, with 97.8% of cases lying within the target zone for abduction. This is

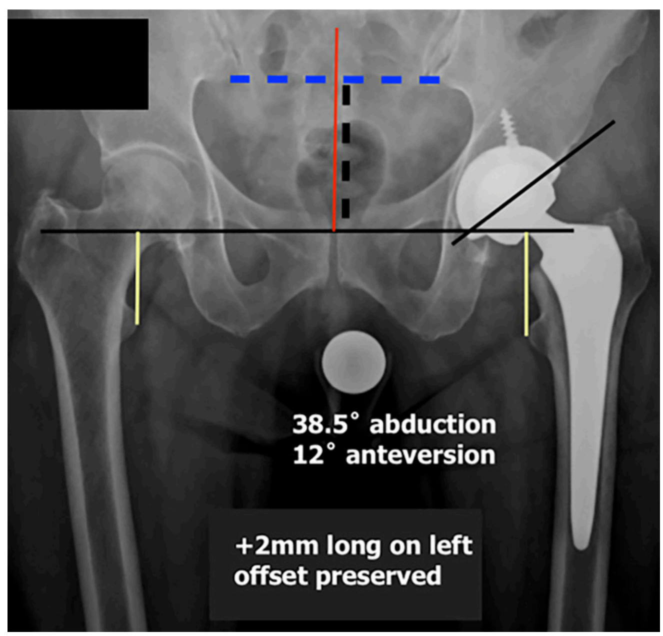

Fig. 6

Intraoperative final radiograph from the patient in Figure 5, an acceptable radiograph based on comparable orientation to the preoperative reference radiograph. Abduction angle measurement is shown. Using the interteardrop line drawn (black transverse line), the limb length can also be assessed.

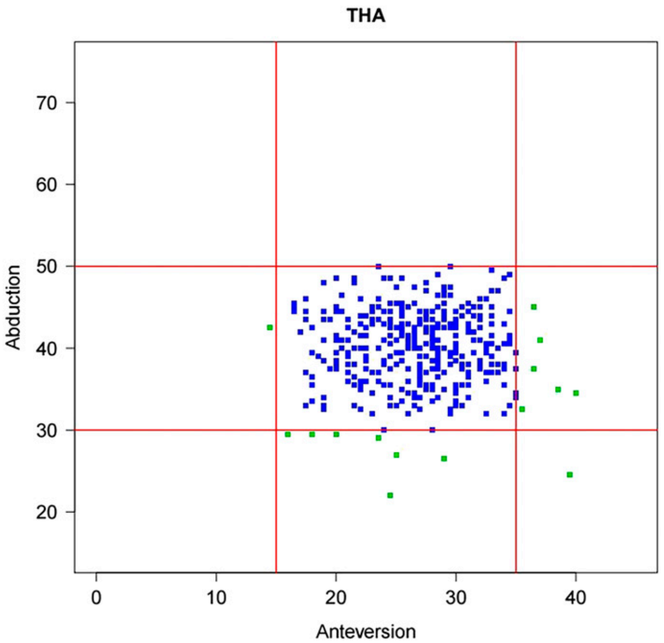

Fig. 7
Scatterplot of mean abduction and anteversion angles: 97.8% of cups were positioned within 30° to 50° of abduction and 95.7% were within 15° to 35° of anteversion. THA = total hip abduction.

higher than previously reported studies. Importantly, the 2.2% of patients with cups that measured outside the abduction target zone were known at the time of the surgical procedure and were deliberately not changed on the basis of clinical grounds of range-of-motion testing and patient factors such as advanced age or bone fragility. It was anticipated that these patients were not going to be extremely active, that their life expectancy was limited, and that dislocation was unlikely given stability to range-of-motion testing.

A review of postoperative radiographs demonstrated that 93.5% of postoperative abduction angles and 98.1% of postoperative anteversion angles were within 5° of their intraoperative measurement. Cases with a larger variation could be accounted for when pelvic tilt is considered. We found that as an image demonstrated more of a pelvic inlet orientation, the abduction angle and anteversion were reduced (Fig. 8).

Despite carefully positioning and securing the patient on the operating room table, intraoperative radiographs were repeated in 88% of cases because the first intraoperative radiograph did not match the reference preoperative radiograph. This suggests that it is very difficult to know the position of the pelvis when the patient is positioned using standard techniques. We have found that we must standardize the pelvic inlet view in the preoperative radiograph to match the intraoperative radiograph to obtain precise acetabular component positioning.

Although digital radiography is used to help the surgeon to assess appropriate cup position, intraoperative range-of-motion testing is essential in assessing the stability of the hip joint[46]. Relying on the traditional safe zone measurements alone could allow impingement and dislocation risk to be overlooked, and multiple recent reports have supported this theory[23,46]. In our current study, 3% of patients had cups positioned within the traditional safe zone yet failed intraoperative range-of-motion testing secondary to neck-rim impingement. At this point, historically, without a radiograph to tell the surgeon that limb length and offset were acceptable, this impingement issue would be solved by adding length via the femoral head, which could lead to overlengthening. This observation confirms that obtaining ideal cup position in isolation does not provide the entire solution for instability in total hip arthroplasty; strict impingement and range-of-motion testing are critical.

Until we can accurately measure and can precisely control femoral anteversion, it appears, based on our extremely low rate of dislocation, that we would therefore redefine being in the safe zone to mean that components are positioned on the basis of generally accepted parameters and the hip passes simulated functional range-of-motion testing. The 1 dislocation reported in this study also emphasizes the importance of range-of-motion testing for the final determination of intraoperative stability. The senior author has added adduction to the standard extension and external rotation maneuver to test for posterior impingement and anterior instability. At this extreme, pressure is applied to the posterior aspect of the greater trochanter to confirm that the prosthetic head component is not perched anteriorly and thus on the verge of dislocating. There have been no additional dislocations in our ongoing series, to our knowledge.

As we move into an era in which technology is increasingly relied upon for certain acknowledged advantages, cost weighs heavily on decision-making. Digital imaging technology appears to meet this cost-effectiveness test. In fact, this technique can be used with any portable x-ray machine and digital flat panel detector, which most facilities already have. A pelvic CT scan for preoperative planning is currently of theoretical clinical value and is associated with a radiation exposure of 15 mSv[47]. In contrast, an average case using digital radiography (3 images) would use approximately 0.9 mSv, as digital radiography is associated with approximately 50% less radiation exposure compared with traditional chemically processed radiographs (0.6 mSv)[44,45]. Moreover, intraoperative fluoroscopy is sometimes used in the lateral decubitus position, but cannot provide a reliable full anteroposterior pelvic radiograph. The use of digital radiography to measure cup position, in our experience, adds only 2 to 4 minutes to the operative time and minimizes interference with workflow. It is reported that roughly 3 seconds of fluoroscopy is equivalent to 1 digital radiography image[48,49]. Therefore, when comparing radiation exposure of digital radiography to the total time of fluoroscopy typically used in anterior total hip

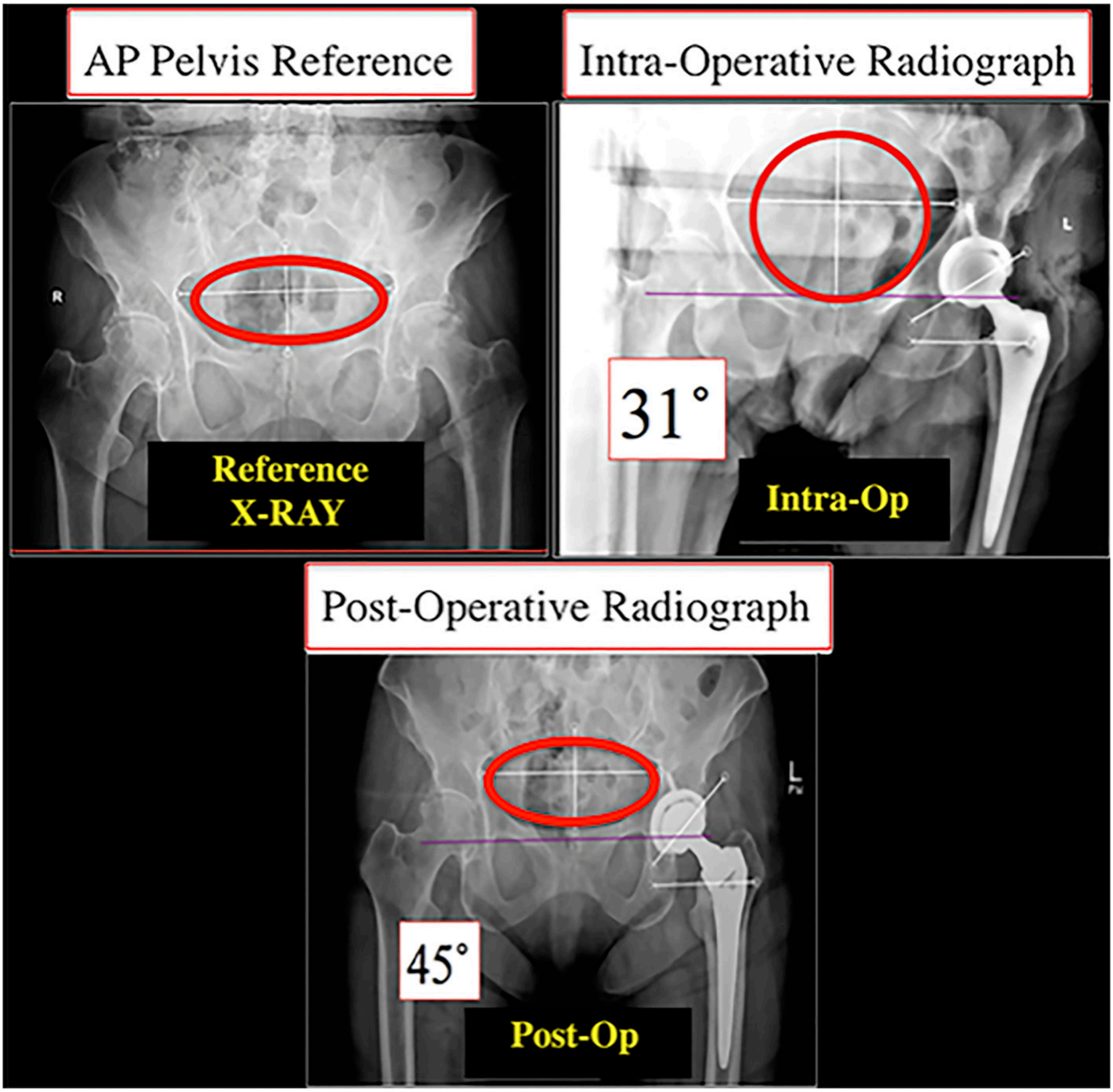

Fig. 8

An example of how pelvic tilt influences intraoperative digital radiography. The tilt on the intraoperative radiograph did not match that on the preoperative radiograph. The more extreme inlet orientation projects an abduction angle of 31°. The postoperative abduction angle, with the reduced outlet view, demonstrated the preferred and derived abduction angle of 45°. AP = anteroposterior.

arthroplasties as reported in the literature (24 seconds), digital radiography (averaging 3 radiographs per case) is much lower[50].

This study did have limitations. First, surgeon skill and ability to obtain accurate intraoperative acetabular radiographic measurements is an important factor in achieving successful results. Second, there is the potential for being inaccurate when attempting to extrapolate 3-dimensional positioning data from a 2-dimensional image. However, we believe that our data indicate that, through accurate measurements and pelvic orientation matching, reliable and reproducible results can be achieved. In addition, the need to make adjustments to the table position to obtain proper orientation of the pelvis can be viewed as cumbersome and time-consuming. For each case, an x-ray technologist is needed to set up the equipment in the operating room before the procedure and to check the system batteries, and the technologist must be immediately available when a radiograph is needed. These factors contribute to increased resource utilization compared with traditional total hip arthroplasty without radiographs. We believed that the benefits far outweighed the few extra minutes of operating room time and that additional radiation exposure was still well under the threshold for current C-arm use for anterior-approach total hip arthroplasty[50].

The immediate feedback of digital radiography has the potential to refine the surgeon's understanding of the relationship of osseous landmarks to cup position. Together with strict range-of-motion testing, digital radiography during total hip arthroplasty has led to predictable postoperative cup positioning as well as a very low dislocation rate in our cohort. ■

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