CLINICAL ORTHOPAEDICS AND RELATED RESEARCH
Number 465, pp. 100–105

Computed Tomography-based Surgical Navigation for Hip Arthroplasty

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Component malpositioning and postoperative leg length discrepancy are the most common technical problems associated with total hip arthroplasty (THA). Surgical navigation offers the potential to reduce the incidence of these problems. We reviewed 317 patients (344 hips) that underwent THA using computed tomography-based surgical navigation, including 112 THAs using a simplified method of measuring leg length. Guided by the navigation system, cups were placed in 40.8° ± 2° of operative abduction (range, 35°–50°) and 30.8° ± 3.2° (range, 19°–43°) of operative anteversion. We subsequently measured radiographic abduction on plain anteroposterior pelvic radiographs and calculated abduction and anteversion. Radiographically, 97.1% of the cups were in the safe zone for abduction and 92.4% for anteversion. The mean incision length was less than 8 cm for 327 of the 344 hips. Leg length change measured intraoperatively was 6.6 ± 4.1 mm (range, –2–22), similar to measurements from the pre- and postoperative magnification-corrected radiographs. Computer assistance during THA increased the consistency of component positioning and allowed reliable measurement of leg length change during surgery.

Level of Evidence: Level IV, therapeutic study. See the Guidelines for Authors for a complete description of levels of evidence.

Among the major complications of hip arthroplasty are sequelae from acetabular component malpositioning[4,7,14] and excessive leg lengthening.[22] Acetabular component malpositioning is associated with instability, impingement, and accelerated wear and may lead to early revision.[21] The variation in pelvic positioning during surgery prevents consistent accurate acetabular component placement using mechanical guides.[27,29,30] Many previous methods of measuring leg length change during surgery have been used, ranging from mechanical devices to simple visual estimation with rulers.[16,23,26,32,33] Difficulties with both accurate cup positioning and leg length change measurement are accentuated by the trend toward smaller incisions, further limiting visualization of local anatomy.[16,23,26,32,33] Both acetabular component positioning and leg length change measurement during surgery may be improved by the application of surgical navigation to THA.

Computed tomography (CT)-based navigation is frequently used for THA.[2,14,19] This method uses preoperative CT imaging to create three-dimensional models of the hip joint to be replaced and to simulate placement of the prosthetic components before surgery. The method also allows for precise preoperative prediction of the leg length change that would occur with the surgical plan as well as the theoretical bone and prosthetic limits to range of motion of the hip that would result from the proposed surgery. Using this method, it is also possible to confirm accuracy of the navigation at the time of surgery. Also, surgery can easily be performed in the lateral position without having to reposition the patient (one-stage setup). In addition, pelvic deformities resulting from prior surgery or developmental abnormalities that distort the typical landmarks can easily be handled by CT-based navigation.

We asked whether CT-based surgical navigation could provide reliable component positioning and whether a new method of intraoperative assessment of leg length would be reliable.

MATERIALS AND METHODS

We prospectively followed 317 consecutive patients (344 THAs) in whom component positioning was established with the assis-

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One author (TME) has received funding from the Research Funding Awards Program of the New England Baptist Hospital. One author (MT) has received funding from the Swiss National Foundation (SNF).
Each author certifies that his institution has approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent was obtained.
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DOI: 10.1097/BLO.0b013e3181591c7d

tance of CT-based surgical navigation. In the same time frame, 37 procedures (10.7%) were not performed with CT-based surgical navigation. In eleven of these cases, retained hardware did not allow for CT based navigation, in ten cases the registration was either unsuccessful or inaccurate. In five patients the intraoperative findings or circumstances (eg insufficient bony anchorage of the cup) led the surgeon to position the component differing from the navigation plan. In four patients a preoperative hip fusion precluded the use of surgical navigation and in one case the reference frame accidentally moved during the case after registration had already been established. Finally, six cases were performed without the use of CT-based surgical navigation for reasons that were not recorded.

Among the 344 hips, 198 (58%) procedures were performed in men and 146 (42%) in women (Table 1). There were 209 (61%) left hips and 135 (39%) right hips; the mean patient age at the time of surgery was 56.1 ± 11.7 years (range, 19.1–85.3 years) (Table 1). Three hundred twenty-seven cases (95.1%) were performed through a superior capsulotomy[17–19] with a mean incision length of 7.7 ± 1.5 cm (range, 5–18 cm). During the procedure, reference frames were percutaneously affixed with a two-pin technique. For the pelvic frame, two Steinmann pins were drilled into the lateral aspect of the ipsilateral iliac crest. Using external fixateur bars and customized adapters, the reference frames equipped with reflective spheres are subsequently attached to the pins. All procedures were then navigated using optical tracking algorithms. All cases were navigated with a CT-based navigation algorithm (VectorVision Build 274 prototype; BRAINLAB AG, Helmstetten, Germany).

TABLE 1. Demographic Data

Parameter	Number of Hips (n = 344)
Gender	
Female	146 (42.4%)
Male	198 (57.6%)
Age (mean ± SD)	56.1 ± 11.7 years (range, 19.1–85.3)
Side	
Left	135 (39.2%)
Right	209 (60.8%)
Diagnosis	
Osteoarthritis	247 (71.8%)
Dysplasia	62 (18%)
Osteonecrosis	11 (3.2%)
Posttraumatic osteoarthritis	10 (2.9%)
Legg-Calvé-Perthes disease	7 (2.0%)
Rheumatoid arthritis	5 (1.5%)
Slipped capital femoral epiphysis	2 (0.6%)
Surgical Approach	
Superior capsulotomy	327 (95.1%)
Modified direct lateral	14 (4.1%)
Superior capsulotomy extended	1 (0.3%)
Trochanteric slide	1 (0.3%)
Incision length in superior capsulotomy cases (mean ± SD)	7.7 ± 1.5 cm (range, 5–18)

SD = standard deviation

During this consecutive series of THA, we introduced a new software algorithm for calculation of leg length change and used this algorithm in the final 112 consecutive procedures. The employment of the leg length measurement in the last 112 cases required an additional femoral reference frame positioned at the lateral aspect of the ipsilateral distal femur. The fixation technique was analogous to that of the pelvic reference frame and the distal localization of the femoral reference frame was chosen to avoid spatial interference with the acetabular reamer and the cup impactor. The pelvic coordinate system was registered by surface data points acquired from the bony pelvis and transferred onto the pelvic surface of the computer model. The femur position was registered into the software by holding the leg in neutral extension position while the computer registered the position of the pelvic and femoral frames. The change in leg length was measured by again holding the leg in exactly the same position, as directed by the navigation system through the two frames, after the trial and final reconstructions. The measurement of the final leg length change was repeated 3 times and the mean of these measurements was considered the true leg length change.

During surgery, we implanted the acetabular cup, respecting the conclusions of Murray[20] and the recommendations of Lewinnek et al,[15] who had described a so called safe zone for implantation of the cup. This safe zone was defined as a radiographic anteversion of 15 ± 10° and a radiographic abduction of 45 ± 10°. Thus, knowing the navigation system uses operative anteversion and abduction, we aimed for an abduction angle of 41° and an anteversion angle of 30° as measured by the navigation system.

Postoperatively, we obtained a set of radiographic views, including anteroposterior (AP)-pelvis, AP-hip, lateral and false profile views. One author (TME) measured acetabular cup abduction on the pelvic radiograph using the interteardrop line as a horizontal reference. The interteardrop line was the horizontal reference as described by Callaghan et al[6] and the distance from the most proximal point of the lesser trochanter to this horizontal line was measured (Fig 1). The radiographic measurement was compared to the abduction measurement by the navigation. Subsequently, we applied the recommendations of Murray,[20] who showed anatomical, operative and radiographic definition of acetabular abduction and anteversion are all different parameters. Depending on the plane and axis, the acetabulum can have different spatial arrangements and therefore it has to be clarified, which definition of abduction and anteversion is used. Murray developed equations and nomograms to relate the three definitions and recommended using operative anteversion to describe positioning of acetabular components.[20] Our navigation algorithm utilized operative abduction. From this data, we calculated radiographic abduction using Murray's equations and then compared that abduction to measurements from plain AP-pelvis radiographs. We measured cup anteversion using the navigation system, but not radiographically. Radiographic anteversion as defined by Murray could again be calculated from the navigation system's operative anteversion.[20]

Leg length change on radiographs was obtained by comparing pre- and postoperative radiographs that were normalized for magnification from the diameter of the implanted acetabular

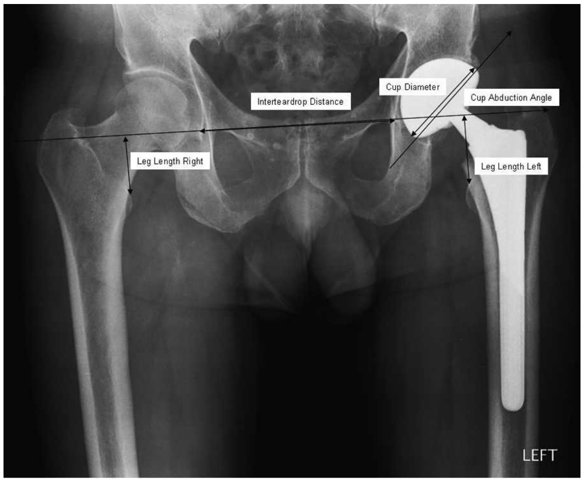

Fig 1. This anteroposterior pelvic radiograph shows the measurement of cup abduction and leg length change on a postoperative image.

component. Leg length change measured on the radiographs was then compared with the leg length change measured by the navigation system.

We examined parameters for normal distribution with the Kolmogorov-Smirnov test. The normally distributed leg length changes were compared using the Student's t-test; the nonnormally distributed cup abduction measures were compared with the Mann-Whitney U-test. P-values of ≤ 0.05 were considered significant.

RESULTS

Surgical navigation resulted in reliable positioning of the acetabular component. The mean cup abduction measured by the navigation system was 40.8° ± 2° (mean ± SD; range, 35°–50°; Table 2). The mean measured radiographic cup abduction angle was 43.6° ± 3.6° (mean ± SD; range, 33°–54°; Table 2) and the calculated radiographic abduction was 45.2° ± 2.2° (mean ± SD; range, 38°–56°). Three hundred forty-three cups (97.1%) in the measured angle and 341 cups (99.1%) in the calculated radiographic abduction were positioned in the safe zone. In comparison, the calculated radiographic abduction was ($p < 0.05$) higher than the radiographic abduction. Operative anteversion angles measured by the navigation system showed a mean of 30.8° ± 3.2° (mean ± SD; range, 19°–43°). Calculating radiographic anteversion from these results, we found a mean anteversion of 22.8° ± 2.4° (mean ± SD; range, 14°–30°) with 318 cups (92.4%) positioned in the safe zone (Table 2).

Analogous to component positioning, the new method of intraoperative assessment of leg length provided reliable results. The preoperative leg length discrepancy of –4.8 ± 5.8 mm (range, –29.8–9.7) was corrected to a postoperative leg length difference of 1.3 ± 5.3 mm (range, –20.3–15.3) (Table 2). Thus, the radiographically measured change was 6.1 ± 4.3 mm (range, –5–20) and the change measured by the navigation system was 6.6 ± 4.1 mm (range, –2–22). The difference between the leg length

TABLE 2. Cup Position and Leg Length Measurement

Parameter	Measurement Results (n = 344)
Cup Abduction	
Navigation data	40.8° ± 2° (range, 35°–50°)
Radiographic data	43.6° ± 3.6° (range, 33°–54°)
Safe zone (≥ 30 and ≤ 50)	334 (97.1%)
Calculated radiographic data	45.2° ± 2.2° (range, 38°–56°)
Safe zone (≥ 30 and ≤ 50)	341 (99.1%)
Cup Anteversion	
Navigation data	30.8° ± 3.2° (range, 19°–43°)
Calculated radiographic data	22.8° ± 2.4° (range, 14°–30°)
Safe zone (≥ 5 and ≤ 25)	318 (92.4%)
Leg Length Measurement (n = 112)	
Preoperative LL difference	–4.8 ± 5.8 mm (range, –29.8–9.7)
Postoperative LL difference	1.3 ± 5.3 mm (range, –20.3–15.3)
Radiographic measurement of LL change (mean ± SD)	6.1 ± 4.3 mm (range, –5–20)
Navigation system calculation of LL change (mean ± SD)	6.6 ± 4.1 mm (range, –2–22)
Difference between methods (mean ± SD)	–0.5 ± 1.7 mm (range, –5–3.9)
p value	0.34

SD = standard deviation; LL = leg length change measured postoperatively using radiographs and the leg length change measured intraoperatively using navigation was −0.5 ± 1.7 mm (mean ± SD; range −5–3.8 mm; $p = 0.34$; Table 2, Fig 2).

DISCUSSION

Complications after THA are frequently the consequence of malpositioned components or inequality in leg length after surgery. Thus, control of component implantation and leg length change during the procedure is crucial. Surgical navigation offers promising options to monitor these important parameters during the case and might assist in achieving reliable and reproducible results for cup implantation and leg length measurement. We asked whether CT-based navigation allowed reliable component positioning and measurement of leg length changes.

Readers should consider several study limitations. First, measurements from plain radiographs are susceptible to errors.[24] These can derive from variation in positioning of the pelvis relative to the plane of the film and centering of the xray beam.[29,30] We used the acetabular component for magnification correction of the AP pelvis radiographs. Another option would have been to use the femoral head, the diameter of which is also known. However, ceramic-on-ceramic bearings had been used in the majority of patients. It is not possible to measure the diameter of these bearings on plain radiographs. By contrast the diameter of the acetabular shell is easily measured on plain radiographs and was used as a method of correcting for magnification. Second, on an AP pelvis image, the xray beams are not perpendicular to the cup because the source of the beam is centered on the midline of the pelvis. The divergence of the xray beams can reduce the accuracy of the magnification correction and angular measurements. Apart from the orientation of the xray beam, pelvic tilt or rotational malpositioning influences reliability of measurements performed on conventional radiographs.[3,8,10,20,27,30,34] Third, acquisition of landmarks during navigation can be erroneous.[2,13] For leg length change measurement the tolerance for these errors is relatively high. For example, as a result of simple geometric calculation, if the orientation of the pelvic coordinate system was achieved with an error of 5°, this error would only affect leg length change measurement by 1%. Therefore, the error in measurement of an intraoperative leg length change of 10 mm would only be 0.1 mm, so this potential error does not appear important. Fourth, in prior studies, attempts have been made to calculate cup anteversion from plain xrays.[1,31] We believe acetabular anteversion cannot be reliably measured on plain radiographs. Ackland et al[1] described a mathematical approach to calculate anteversion from plain xrays. Knowing planar anteversion and vertical tilt of the cup, they provided nomograms for calculation of true anteversion. However, since publication of this paper in 1986 we have learned, and several authors[27,30] have demonstrated pelvic tilt largely influences the estimation of acetabular position on plain radiographs. Thus, without knowing the pelvic tilt, this method cannot be used to reliably calculate for anteversion. It is evident the most accurate method to ascertain cup position calls for a postoperative CT imaging. We have the data necessary to accurately calculate acetabular anteversion based on CT-radiograph matching techniques and this is a major focus of current studies. Postoperative CT scans would furthermore be beneficial to determine accuracy of the navigation system by obtaining more exact measurements and by knowing precision and bias. Finally, although the algorithm reported in this study enabled us to measure leg length change during surgery, offset change is another critical parameter that could not be measured with the software setup at that time.

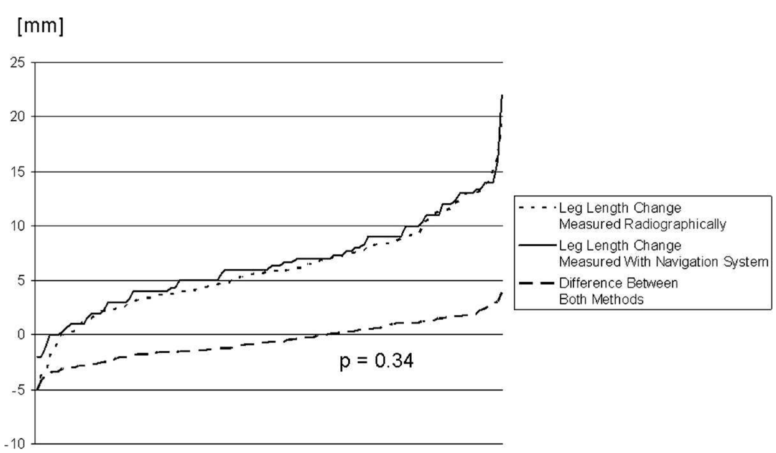

Fig 2. The results for the changes in leg length measured on radiographs and calculated by the navigation system are shown. The solid line represents the measurements performed by the navigation system, whereas the dotted line shows the radiographic measurements. The closeness of the lines reflects the closeness of the measurements. The dashed line below shows similar ($p = 0.34$) mean difference between both measurement methods.

We found a difference between the measured radiographic and the calculated radiographic abduction. This difference is the result of a combination of measurement errors on plain radiographs and errors in both registration and tracking. At this point, postoperative CT imaging could have provided information on which method was more accurate and reliable. Nonetheless, using our current cup position measurement capability, 97.1% measured radiographically and 99.1% calculated radiographically were inside the safe zone regarding abduction, and 92.4% of the cups were placed in the safe zone regarding anteversion. However, readers should consider these were single measurements performed by a single examiner. Repeated measurements with more than one examiner and a subsequent controlled analysis of inter- and intraobserver bias would have enhanced the scientific rigor of the study. When compared to the current literature, these findings suggest the application of surgical navigation improves the surgeon's ability to place components more reliably and with greater consistency. Saxler et al[25] described 105 manually implanted cups and reported only 27 cups were inside the safe zone. Kalteis et al[11] compared manual and CT-guided cup implantation and reported only 14 of 30 manually implanted cups were in the safe zone, whereas 28 of 30 CT-guided cups were implanted correctly. Leenders et al[14] ascertained cup abduction in a historical non-navigated and two prospective randomized groups with and without navigation. The navigated group had 98% of the cups in the planned range of 40 to 55 degrees and showed less variability in abduction than the historic and less variability regarding abduction than the concomitantly studied non-navigated group. Other authors also found good results with manual implantation. Sotereanos et al[28] reported 4% abduction outliers and reproducible cup orientation in their study. Hart et al[9] investigated component positioning in two surgical approaches without navigation, and had a mean abduction of 42.3 degrees with a mean anteversion angle of 13.6 degrees in the mini-posterior group and an average cup inclination angle of 42.4 degrees with a mean anteversion angle of 13.6 degrees in the conventional group. We believe that although it is possible to safely implant cups manually, surgical navigation is a beneficial tool to reliably position the components.

Measuring leg length changes during surgery also appears reliable since we observed no differences between leg length change measured using navigation during surgery and leg length change measured radiographically. Because leg length discrepancy is one of the most common problems patients perceive after hip arthroplasty, the advent of a simple and reliable method of controlling leg length change during surgery may be of great benefit to both surgeons and their patients. There are other studies suggesting mechanical methods are also useful in measuring leg length change during surgery.[5,16,23,33] Conversely, Konyves and Banister[12] reported on the difficulties of accurately measuring leg length change during surgery using mechanical means. Nonetheless, there is no doubt an additional tool for leg length measurement may be helpful.

Our data suggest both component positioning and leg length change can be well controlled using surgical navigation even as smaller incisions are being employed.

Acknowledgments

We thank Dr Martin Haimerl and Gregor Tuma (BrainLAB AG, Orthopedic Solutions) for their contributions to this project.

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