A new CT method for measuring cup orientation after total hip arthroplasty

A study of 10 patients

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Background It is difficult to assess the orientation of the acetabular component on routine radiographs. We present a method for determining the spatial orientation of the acetabular component after total hip arthroplasty (THA) using computed tomography.

Patients and methods Two CT-scans, 10 min apart, were obtained from each of 10 patients after THA. Using locally developed software, two independent examiners measured the orientation of the acetabular component in relation to the pelvis. The measurements were repeated after one week. To be independent of the patient position during scanning, the method involved two steps. Firstly, a 3D volumetric image of the pelvis was brought into a standard pelvic orientation, then the orientation of the acetabular component was measured. The orientation of the acetabular component was expressed as operative anteversion and inclination relative to an internal pelvic reference coordinate system. To evaluate precision, we compared measurements across pairs of CT volumes between observers and trials.

Results Mean absolute interobserver angle error was 2.3° for anteversion (range 0–6.6°), and 1.1° for inclination (range 0–4.6°). For interobserver measurements, the precision, defined as one standard deviation, was 2.9° for anteversion, and 1.5° for inclination. A Student's t-test showed that the overall differences between the examiners, trials, and cases were not significant. Data were normally distributed and were not dependent on examiner or trial.

Interpretation We conclude that the implant angles of the acetabular component in relation to the pelvis could be detected repeatedly using CT, independently of patient positioning.

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Measurement of the orientation of acetabular component in total hip arthroplasty (THA) is a three-dimensional problem which requires accurate determination of both the pelvic and socket orientations. This is difficult to achieve on routine planar radiographs. We thus developed a method for determining the orientation of the pelvis and the acetabular component using CT and a two-step protocol. We evaluated the precision of this method by repeated CT examinations of the same patients, and by repeating the measurements at one and the same examination.

Patients and methods

10 patients were included (median age 62 (37–81) years, 7 women), all of whom had undergone primary THA with the cemented Charnley implant

system (DePuy, Warsaw, IN). Informed written consent was obtained from all patients. The study was approved by the Karolinska Institute Ethics Committee (North).

CT scanning

We used a spiral CT scanner (Picker 5000, Philips Medical Systems, Cleveland, OH). Scans were acquired with 5-mm collimation and a pitch of 2, at 175 mA, 120 kV, 1 s scan time from iliac crest to tip of the prosthesis stem, except over the cup where 2-mm collimation, at 200mA, was used. Volume data were reconstructed with 5-mm increment or 1.5-mm increment, respectively. The radiation dose for the scans was calculated to be 0.8 mSv, comparing favorably with standard radiographic examinations of THA. Two CT scans with an interval of 10 min were obtained from each patient in the first postoperative week after THA. Between the scans, the patient was removed from the bed of the CT scanner and subsequently repositioned. Volume data sets were transferred to a Linux-based mobile workstation (Dell precision M50).

Tools used for image volume analysis

For image post-processing, a locally developed 3D volume fusion tool was used (Noz and Maguire 1988, Noz et al. 2001). This tool has been validated extensively (Maguire et al. 1991, Gorniak et al. 2003), including studies on THA (Olivecrona et al. 2002, 2003a, b, c).

The user interface presents arbitrarily chosen slices from two volumes simultaneously. Two larger views representing corresponding slices in one of the planes (axial, sagittal, and coronal) or six smaller views representing corresponding slices in all three planes can be displayed. Two window width/level settings can be displayed in different color scales. The lower window can be used for viewing the skeletal structure, while the higher window allows a simultaneous view of metal (Figure 1). There is also a separate 3D-isosurface display on which the landmarks can be displayed (Figure 2). Landmarks are chosen on concurrently viewed slices which exhibit the same physiological or implant component feature or structure. When a landmark is chosen, the corresponding point in the 3D volume is recorded in distance units (mm in this case) independently of any voxel location, and a sequence number is generated. Landmarks are chosen by either designating a single point (a point landmark) or with the aid of a sphere. Point landmarks are generated by selecting a point of interest with the pointing device. The 3D sphere superimposes the contours of a three-dimensional sphere on the images in all three planes (axial, coronal and sagittal), together or separate. The sphere is moved into the correct position in the volume by pushing the sphere in any plane, i.e. positioning the pointing device within the sphere contour and dragging. When the sphere has been moved into a satisfactory position, the user generates a landmark, which represents the 3D coordinates at the center of the sphere. The size of the sphere can be chosen by specifying the radius before entering sphere mode, or interactively during processing.

Standard orientation of the pelvis

The pelvis has a well-defined coronal plane, usually referred to as the McKibbin plane, which includes the superior iliac spines and the pubic tubercles (McKibbin 1970). Orthogonal to this is a plane through the tuber os ischii. In this study, the following sequence was used to bring the pelvis from the orientation in the CT-scanner (Figure 3a) to a standard pelvic orientation (Figure 3e): alignment of the McKibbin plane horizontally (Figure 3b), changing of the view angle from axial to coronal (Figure 3c), rotation around the screen anterior-posterior axis until the left and right tuber os ischii were aligned on a horizontal line (Figure 3d), and changing back to axial view (Figure 3e). This sequence locks all three degrees of rotational freedom between the axes of the screen and the anatomical axes of the pelvis and aligns these axes.

To accomplish this, a submodule for standardization of orientation of an object using the 3D isosurface display has been added to the locally developed software. In this module, the 3D volumes can be rotated, scaled, and viewed from an arbitrary direction. Rotations, either three-dimensional or around a screen axis, are generated by dragging the pointing device over the image. A movable horizontal line which is independent of the volume being displayed is superimposed on the screen to provide a fixed reference guide. By pressing one of two menu buttons provided, the operator can rotate the volume 90° clockwise or

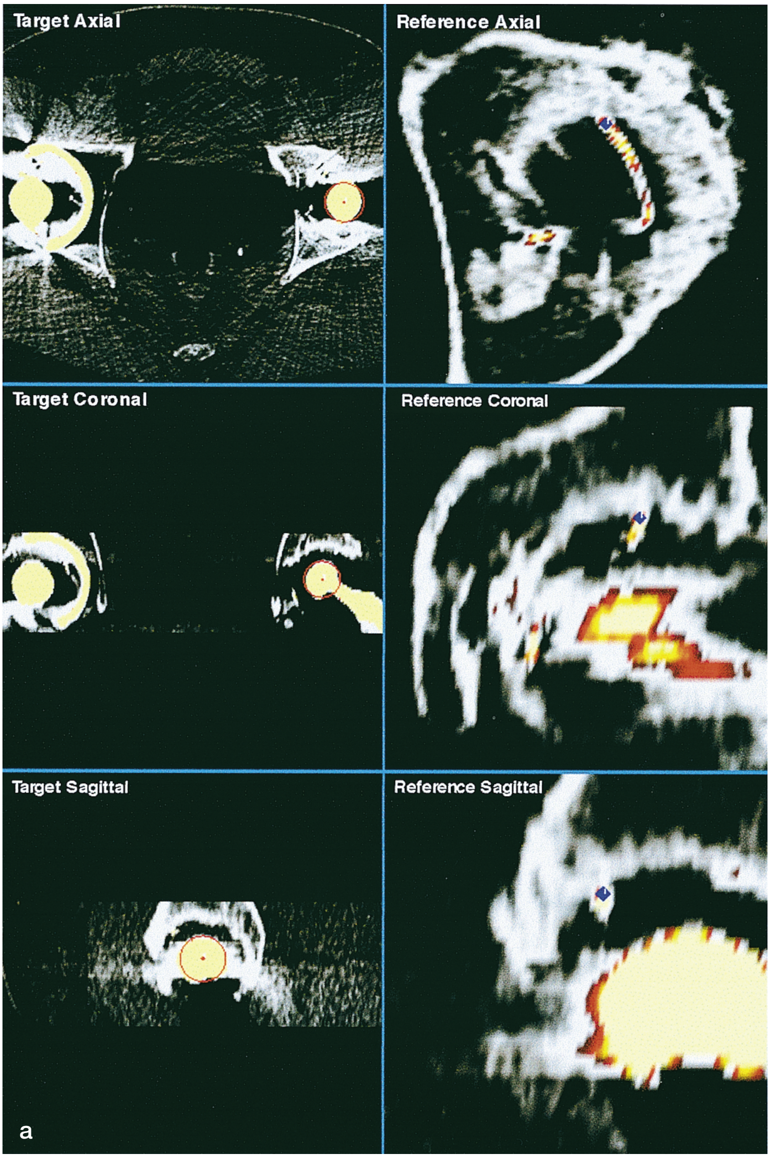
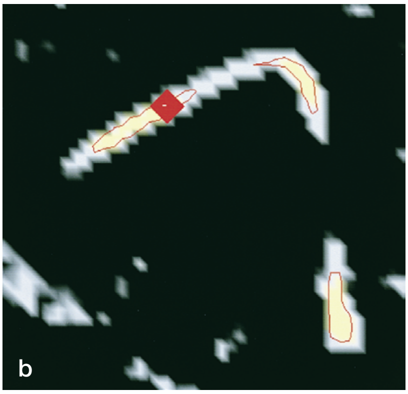


Figure 1. Detection of the acetabular component. Landmarks are placed in concurrently viewed 2D slices. Dual window/width scales: high attenuating metallic thread in acetabular component displayed in yellow, lower attenuating bone displayed in grayscale.
a. Three simultaneous orthogonal views of a patient with an earlier inplanted uncemented THA on the right side and the cemented THA on the left side. The left three windows demonstrate the 3D sphere that can be used for detecting spherical objects. To the right, the metallic thread in the cup is seen with a landmark (blue).
b. Close-up of axial view.



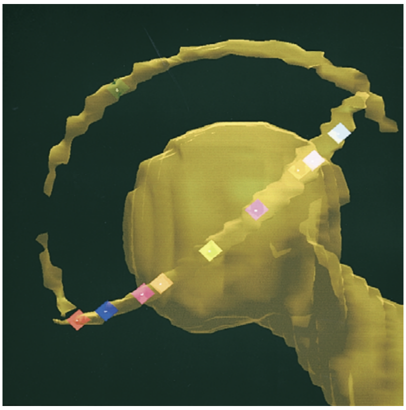


Figure 2. 3D isosurface display of cup thread with landmarks illustrating the landmark pattern of the socket. This information is processed into orientation of the acetabular component by a separate software module.

counterclockwise around the left-right screen axis, this changing between axial and coronal view. The results are saved in matrix form representing the rotation which brought the orientation of the object in the original CT volume into the standard orientation, and the transformed volume data set is also saved in the standard orientation.

Image volume analysis

All measurements were made by two independent examiners, a resident in radiology (examiner 1) and an orthopedic surgeon (examiner 2). Both examiners repeated their measurements after one week. The time for analysis of each volume was restricted to 15 minutes, which we considered to be reasonable in a clinical situation. Given this time limit, the number of landmarks chosen on the thread was set to 10 or less.

For each patient volume, a 3D view of the pelvis rotated to standard pelvic orientation, and the corresponding standard pelvic orientation matrix (SPO matrix) was recorded (Figure 3a-c). We used simplified 256 × 256 xy volumes, thus lowering the resolution 4 times.

Thereafter, the acetabular component was detected in the original volume (full 512 × 512 xy resolution) by a set of interactively placed landmarks (cup landmark points, CLP). A maximum of 10 points was placed in the part of the cup metallic thread that was parallel to the cup opening, and 1 point in the part of the thread that was perpendicular to the cup opening (Figures 1 and 2).

Calculation of acetabular orientation

To calculate the cup orientation relative to the pelvis, three steps were performed on each set of data.

1. Rotation of the cup landmark point set by applying the corresponding standard pelvic orientation matrix.
2. Calculation of the orientation of an axis perpendicular to the cup opening (the acetabular axis) from the rotated pointset.
3. Expression of the acetabular axis orientation as inclination and anteversion.

All calculations were done by a mathematical submodule that transforms coordinates between different coordinate systems and incorporates an algorithm that computes the best-fit plane from a set of points. The plane is expressed in normal form, i.e. the direction of a vector that is perpendicular to the plane and a distance from origo. In the case of the acetabular component, the plane to be calculated is the plane throught the cup opening. The normal axis to this plane, passing throught the cup center, is referred to as the acetabular axis (Calandruccio 1987). The particular algorithms used have been described previously (Olivecrona et al. 2002, 2003b) and define the plane by elliptical fitting. In addition, the stability of the particular landmark pattern is expressed by condition numbers and individual landmark errors relative to the calculated object (Olivecrona et al. 2003b). When the calculated object is a plane, the error of each cup landmark is expressed as the signed distance in mm between the landmark and the calculated cup plane. The plane condition number, defined as how well the landmarks represent a plane, is a non-dimensional number that can vary between 0 and 1, where small values reflect a landmark pattern close to a plane, and large values reflect landmark patterns far from a plane, e.g. a spherical pattern. The stabilities of the calculated planes were not analyzed in this study.

Three definitions of acetabular component orientation co-exist in common use: the operative, the anatomical, and the radiographic. These reflect the different situations when the orientation is assessed. Murray (1993) has described the different definitions, and has also provided illustrations and nomograms for conversions between the different systems. Briefly, most implant systems uti-

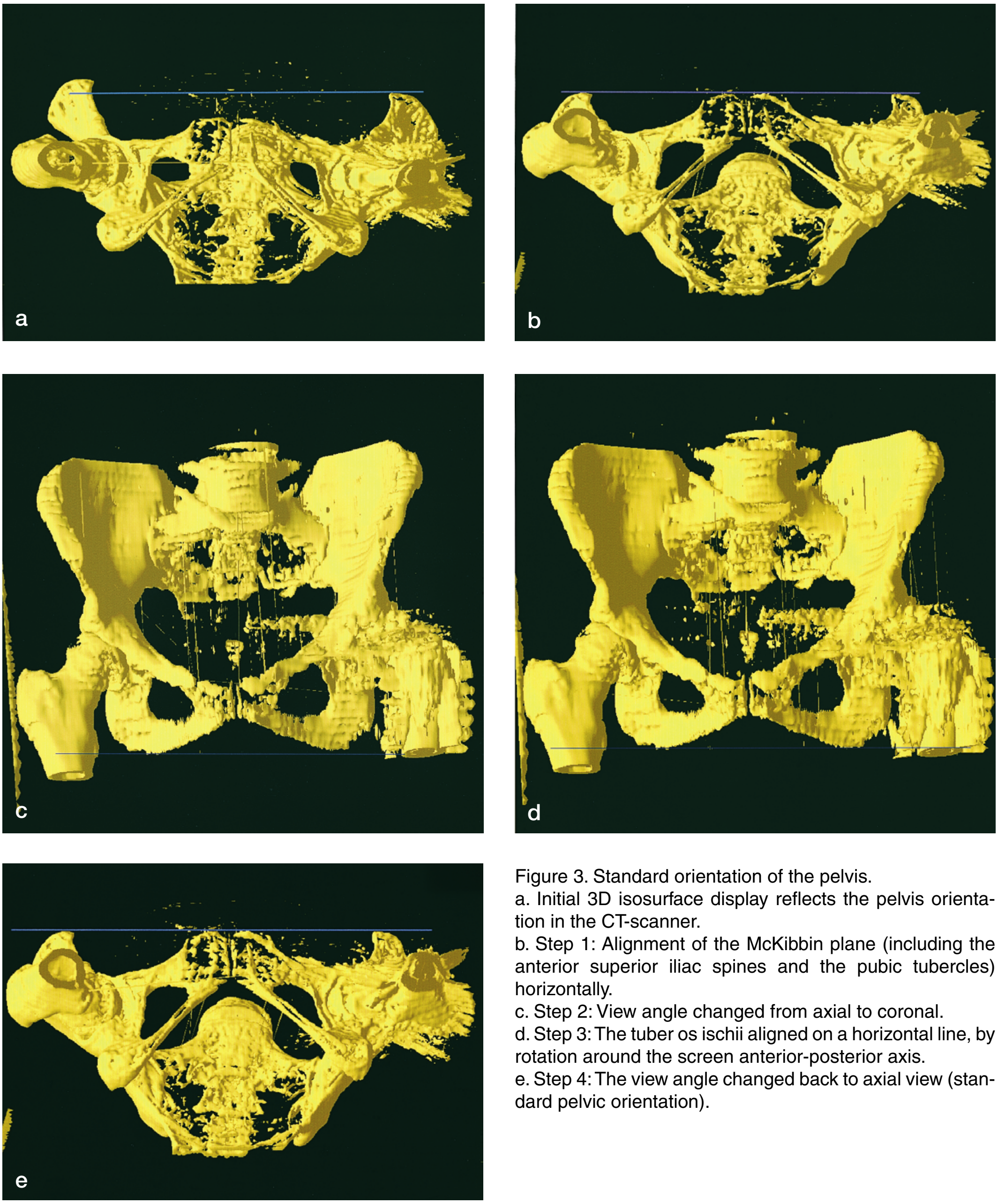


Figure 3. Standard orientation of the pelvis.
a. Initial 3D isosurface display reflects the pelvis orientation in the CT-scanner.
b. Step 1: Alignment of the McKibbin plane (including the anterior superior iliac spines and the pubic tubercles) horizontally.
c. Step 2: View angle changed from axial to coronal.
d. Step 3: The tuber os ischii aligned on a horizontal line, by rotation around the screen anterior-posterior axis.
e. Step 4: The view angle changed back to axial view (standard pelvic orientation).

lize an arrangement of guide rods that aid in alignment of the acetabular component. A typical system has one rod intended to be parallel to the transverse axis of the patient, and one line parallel to the patient's longitudinal axis. Rotations around the transverse axis are intended to alter the anteversion but not the inclination. This is the case in the operative definition of acetabular orientation. Operative anteversion is the angle between the orthogonal projection of the acetabular axis onto the sagittal plane and the longitudinal axis of the patient, i.e. the degree of cup rotation (torsion) around the transverse axis. Operative inclination is the angle between the acetabular axis and the sagittal plane, i.e. cup abduction relative to the sagittal plane. In contrast, the anatomical definition is most closely related to the result when the angles are measured from an axial CT slice. Anatomical anteversion, sometimes referred to as the true anteversion, is the degree of rotation around the longitudinal axis, and can be measured directly on an axial CT slice. Anatomical inclination is the angle between the longitudinal axis and the acetabular axis, and can only be measured directly using 3D data. The radiographic definition relates to what is measured from the projection of the acetabular component onto standard radiographs. Radiographic anteversion is best measured from the ratio between the long and short axes of the elliptical projection of the acetabular opening onto antero-posterior (AP) radiographs. Radiographic inclination is the angle between the longitudinal axis and the projection of the long axis of the cup opening on the AP radiograph. The relationship between these different ways of expressing the acetabular orientation are defined by trigonometric formulae, i.e. they are non-linear. In this study, the operative set of angles was used, as recommended by Murray.

Evaluation of errors

For evaluation of the total error of the method, a total error dataset (TE) was formed, containing measurement errors in degrees of operative anteversion and inclination across the pairs of image volumes (the a- and b-scans of each patient) between observers and trials. TE included 5 subclasses for anteversion and inclination, respectively: interobserver, intraday-observer-1 and -2, and interday-observer-1 and -2. The angle errors in each subclass should ideally be zero in this procedure. The subclasses were individually tested for normality with the one sample Kolmogorov-Smirnov test of Composite Normality (KS test), and also evaluated graphically. Intra- and inter-observer differences were analyzed with a Student's t test. Mean angle error, mean absolute angle errors and standard deviation across volumes were calculated. P-values of less than 0.05 were considered significant.

Since the method involved two user-interactive steps (standard orientation of the pelvis and placing of landmarks on the cup), we explored how much of the total error each step produced. To test the standard pelvic orientation step, a standard pelvic orientation dataset (SPO) was formed by applying the four different standard pelvic orientation matrices corresponding to each patient volume (the examiner 1 and 2, trial 1 and 2 SPO matrices) to one and the same cup landmark file corresponding to the particular patient volume, and repeating this for all patient volumes. This was done by selecting the trial 1 cup landmarks of examiner 1 from each volume and applying corresponding standard pelvis orientation matrices from the four trials to these landmarks, and then calculating the cup angles. This had the effect of applying the different standard pelvis orientation matrices from the 4 trials on the same vector, simulating an image analysis that was error-free at the cup detection step. To test the cup detection step, a cup landmark dataset (CL) was formed by calculating the anteversion and inclination from each trial without first applying the corresponding standard pelvic orientation matrices, thereby simulating an image analysis that was error-free at the standard pelvis orientation step. This procedure is equivalent to applying the identity matrix as SPO matrix, and then calculating the acetabular orientation. The SPO and CL datasets were analyzed within each volume. For both the SPO and CL datasets, the angle errors of anteversion and inclination between the measured axis and the average over the four trials corresponding to each patient volume were calculated, and tested for normality using the KS test. The standard deviation, range, and average deviation from the mean were calculated. The SPO and CL datasets were individually compared using Student's t tests.

Results

One of the patients had significant movement artefacts in one of the volumes. The thread in this volume could not be safely visualized for landmark placement. Consequently, this case was excluded. The resulting analysis was done on the remaining 9 cases. All datasets (TE with subclasses, SPO, CL) had normal distributions graphically and the KS test was insignificant for all populations. All image analyses were performed within the stipulated time limit.

The measured operative anteversion and inclination for the overall evaluation of the method are presented in Table 1. Precision, expressed as one standard deviation, and mean error between measurements are presented in Table 2. The mean of the absolute interobserver angle errors across volumes, i.e. when different examiners measured the different volumes of each patient, was 2.3° (range 0–6.6°) for anteversion and 1.1° (range 0–4.6°) for inclination. A Student's t test showed that the overall differences between the examiners, trials, and cases were not significant ($p \geq 0.05$). There was no significant difference between the angles measured between the two repeated scans of the patients ($p \geq 0.05$). The lowest precision, 2.9° for anteversion and 1.5° degrees for inclination, was found in the interobserver measurements.

The analysis of how much of the total error each step produced is presented in Table 3. Student's t tests showed that the errors due to the first step of the method, standard pelvic orientation, were significantly less overall than for the second (cup detection) step. There were no significant differences between the errors corresponding to anteversion and inclination in the standard orientation step, but the errors for inclination compared to anteversion were significantly less in the cup detection step.

Table 1. Orientation of the acetabular axis, expressed as operative anteversion/inclination, in the 10 patients. Each patient was CT-scanned twice (a and b scan), and each examiner analyzed each scan twice (trials 1 and 2). Angles are given in degrees

Patient/ scan	Examiner 1 Trial 1	Examiner 1 Trial 2	Examiner 2 Trial 1	Examiner 2 Trial 2
1 / a	17.0 / 35.3	17.5 / 33.4	19.0 / 34.0	17.8 / 34.4
1 / b	17.5 / 34.8	16.2 / 34.4	19.9 / 34.2	16.0 / 33.9
2 / a	30.5 / 47.2	27.7 / 47.9	29.3 / 48.6	27.2 / 48.5
2 / b	29.9 / 46.3	26.2 / 49.0	29.9 / 48.4	28.7 / 48.2
3 / a	Excluded	Excluded	Excluded	Excluded
3 / b	Excluded	Excluded	Excluded	Excluded
4 / a	51.8 / 38.0	52.1 / 37.9	48.9 / 38.4	50.0 / 38.8
4 / b	49.6 / 38.2	50.6 / 38.5	50.2 / 39.4	51.4 / 38.6
5 / a	4.5 / 63.5	1.9 / 63.8	5.3 / 61.6	6.7 / 65.0
5 / b	2.0 / 60.8	2.4 / 60.4	0.1 / 60.1	4.8 / 63.7
6 / a	7.2 / 31.7	11.0 / 32.0	13.7 / 32.3	13.2 / 32.8
6 / b	7.5 / 31.0	10.0 / 32.0	12.2 / 31.7	11.0 / 31.8
7 / a	32.0 / 46.6	30.1 / 44.9	33.2 / 47.0	32.2 / 46.4
7 / b	34.4 / 47.8	32.4 / 45.9	36.7 / 48.0	31.5 / 46.9
8 / a	20.8 / 30.4	20.3 / 29.9	22.9 / 31.0	21.1 / 30.9
8 / b	19.5 / 30.6	20.3 / 29.0	21.6 / 31.1	22.2 / 30.6
9 / a	19.9 / 43.3	21.1 / 44.7	24.9 / 43.9	22.0 / 43.3
9 / b	24.6 / 43.5	22.5 / 42.9	24.4 / 43.6	23.0 / 42.9
10 / a	38.4 / 46.9	37.1 / 46.7	43.9 / 47.1	39.1 / 47.9
10 / b	40.2 / 46.2	43.3 / 44.4	43.4 / 44.8	41.2 / 44.8

Table 2. Precision of measurement across pairs of patient volumes of the acetabular axis in the 9 cases. Angles are given in degrees

	Anteversion mean error (SD)		Inclination mean error (SD)	
Intraday examiner 1	–0.5	(2.3)	0.5	(1.4)
Intraday examiner 2	0.1	(2.0)	0.4	(1.1)
Interday examiner 1	0.1	(2.0)	0.5	(1.0)
Interday examiner 2	0.1	(2.8)	0.5	(1.5)
Interexaminer	–0.2	(2.9)	0.5	(1.5)

Table 3. Variations in measurements of the acetabular axis within volumes due to the two steps of the method. Angles are given in degrees

	SD	Minimum	Maximum	Average deviation from mean
Standard pelvic orientation step				
Inclination	0.3	–0.9	0.8	0.2
Anteversion	0.4	–1.7	1.0	0.3
Cup detection step				
Inclination	0.6	–1.7	1.5	0.5
Anteversion	1.6	–4.0	4.4	1.3

Discussion

Potential errors in determining implant orientation on conventional radiographs include differences in pelvic position between examinations and measurements of angles that are outside the exposed plane. To our knowledge, there is no noninvasive radiographic method that can detect implant position relative to bone in three dimensions. Methods such as RSA (Kärrholm et al. 1997) are capable of detecting changes in implant position between examinations, but these changes are always related to the initial examination and cannot determine whether the implant was initially implanted in a good or bad position in the bone. Since the position of the initial implant might affect both migration and wear due to eccentric force distribution, assessment of the initial three-dimensional implant position is important. There are many careful and complex trigonometric radiographic methods for determining the position of the components (Lewinnek et al. 1978, Herrlin et al. 1988, Fontes et al. 1991, Hassan et al. 1995). One common feature of all of these methods is that they are in some way dependent on the patient's positioning during examination. Calculation of the true three-dimensional malposition of the pelvis on conventional radiographs is difficult. Pierchon et al. (1994) stated that the exact amount of anteversion could not be reliably measured.

To make our method independent of patient positioning, the volume analysis was divided into two steps, reorientation of a volumetric image of the pelvis into a standardized pelvic orientation followed by measurement of the acetabular orientation based on a finite set of point landmarks. This basic algorithm could be used for other skeletal structures and implants, but we focused on the pelvis and the acetabular component. Ideally, the standardized pelvis orientation should provide a set of angles meaningful to hip arthroplasty surgeons. The standard orientation of the pelvis that we used places the McKibbbin plane as a coronal plane. This plane has been proposed earlier as a reference plane for measuring acetabular orientation (McKibbin 1970), and can be determined by palpation of landmarks during surgery. It is also the reference plane used in some computer-assisted surgery systems. The second plane, including the tuber os ischii, is the inferior margin of the pelvis. Since the method proposed measures the true orientation of the normal axis to the cup opening, the acetabular axis, as a vector in space, it is possible to express this orientation by any of the commonly used definitions because these are just projections of the acetabular axis. It has been proposed that for measurements after THA, the operative definition should be used (Murray 1993), and this was used in our study. This has the effect that the same measurement system was used during this radiographic follow-up as would have been used in the operating room. The alternative way of measuring the same angles is by use of specialized fluoroscopic equipment with the capability of cephalocaudal angulation, or in the case of operative anteversion (but not inclination) on a true lateral view of the pelvis on planar radiographs. Both of these approaches are impractical, and the precision of such measurements is not known. In THA, CT has mainly been used for preoperative planning and evaluation of periprosthetic bone deficiencies (Robertson et al. 1998). Methods for determination of the orientation of implants using CT have been described (Pierchon et al. 1994, Reinus et al. 1996), but none of these exploit the potential of truly three-dimensional data from CT, and the precision of these systems is unknown.

The 3D orientation of the acetabular component was assessed with a precision of 2.9° for anteversion and 1.5° for inclination across pairs of patient volumes, when these were measured by different examiners. An analysis of the individual steps of the method indicated that most errors occurred during marking of the cup. The errors were due to several factors. The thread in the cup was not perfectly semicircular, which meant that the true orientation of the acetabular axis was not perfectly assessed when landmarks were placed on the thread. Only a hemicircle of the threads was coplanar with the acetabular opening, generating a suboptimal landmark pattern. Optimal configuration would space the landmarks in a circle (Olivecrona et al. 2003b). Such a pattern could be used for most acetabular components. The complete analysis was done on a laptop computer with no magnification of the images. The data used were obtained from a CT machine that was over 5 years old. Current multislice CT techniques, enabling thinner slices and smaller voxels, might improve the precision. The simple protocol for the standard pelvic orientation that was used gave no guidance on how to fine-tune the orientation of the pelvis in the precence of osteofytes or metallic artefacts. The time for analysis of each volume was restricted to 15 minutes. Given this time limit, the number of landmarks chosen on the thread was set to 10 or less. More cup landmarks might have produced less overall error, but the time for analysis would have increased. The stability parameters on individual landmarks and overall cup landmark pattern that was generated automatically along with the results were not used. In one of the 20 scans used for this study, the cup orientation could not be analyzed because the patient moved during the scanning procedure. This is a self-limiting problem, because currently CT is migrating to multislice technique, lowering the scan time by at least one order of magnitude. In subsequent trials, we have not seen a repetition of this problem. Consequently, we think that there is room for improvement.

We make no statement of the accuracy of the system used. During extensive testing, no indications of corrupt basic data were found. However, to formally show the accuracy, the system has to be tested in a model study with known data for comparison. No systematic differences were found between observers and trials, indicating that the method can be safely used in a larger setting.

We conclude that the implant angles of the acetabular component in relation to the pelvis could be detected repeatedly using CT, independently of patient positioning and with a precision of 2.9° for anteversion and 1.5° for inclination.

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