2D measurements of cup orientation are less reliable than 3D measurements

A retrospective study of 87 metal-on-metal hips

Kinner DAVDA[1], Niall SMYTH[2], Justin P COBB[1], and Alister J HART[3]

[1] Imperial College, Charing Cross Hospital, London, UK; [2] Hospital For Special Services, New York City, NY, USA; [3] Royal National Orthopaedic Hospital, Stanmore, UK.
Correspondence: kdavda@gmail.com
Submitted 2014-07-29. Accepted 2014-12-31.

Background and purpose — 2D analysis of metal-on-metal (MoM) hip arthroplasty (HA) has been conducted in several large series on conventional radiographs with the use of Ein Bild Roentegen Analyse (EBRA) software, but there have been no comparisons with 3D analysis in the literature. The main aim of this study was to quantify the agreement in measurements of cup version of large-diameter MoM hips obtained by EBRA and by 3D computed tomography (3D-CT). The secondary aim was to quantify the agreement for cup inclination. Lastly, we wanted to determine the inter- and intra-observer reliability of both methods.

Patients and methods — 87 MoM hips in 81 patients were analyzed for cup inclination and version in 2D on conventional radiographs using EBRA software. The results were compared with 3D measurements using CT.

Results — Cup version was underestimated by EBRA when compared to 3D-CT, by 6° on average with the pelvis supine and by 8° on average with the pelvis orientated to the anterior pelvic plane (APP). For inclination, the mean difference was no more than 1°. 53% of hips were within a 10° safe zone of 45° inclination and 20° version when measured by 3D-CT with the pelvis supine (and 54% with the pelvis in the APP). The proportion was only 24% when measured by EBRA. Inter- and intra-observer reliability of cup version is poorer using 2D analysis than when using 3D-CT.

Interpretation — Errors in version in 2D were due to the difficulty in delineating the cup rim, which was obscured by a large-diameter metal head of the same radio-opacity. This can be overcome with 3D analysis. The present study demonstrates that measurements using EBRA have poor agreement and are less reliable than those with 3D-CT when measuring cup version and inclination in MoM hips.

■

Designed originally to measure migration and wear of the cup in total hip replacement (Ilchmann et al. 1995, Phillips et al. 2002), Ein Bild Roentgen Analyse software (EBRA version 10, University of Innsbruck, Austria) has been increasingly used to measure cup version and inclination in metal-on-metal (MoM) hip arthroplasty (HA) (Langton et al. 2008, 2009, Grammatopoulos et al. 2010, Bolland et al. 2011, Langton et al. 2011). Numerous authors have drawn conclusions based on these analyses, suggesting that abnormal cup version results in increased wear rates (Langton et al. 2010a), higher metal ion levels, and an adverse reaction to metal debris (Langton et al. 2008, 2010, 2011). These reports are of importance to hip surgeons treating patients with a symptomatic MoM HA and to researchers examining the causes of failure in this bearing couple. While EBRA has been shown to measure socket version in metal-on-polyethylene bearing couples with sufficient accuracy (Biedermann et al. 2005), its validity for this application in MoM hips is based on a single laboratory study (Langton et al. 2010b). Its accuracy in the clinical setting when both components are present is unclear, particularly as large-diameter metal heads have been shown to obscure the cup margins on conventional radiographs (Hart et al. 2009).

3D computed tomography (3D-CT) has emerged as a robust method in providing objective measurements of component alignment in hip and knee arthroplasty. It has been shown to be more accurate and reliable than conventional radiographs (Tannast et al. 2005b) and axial CT (Dandachli et al. 2011) in determining the 3D spatial orientation of the acetabular cup. This is because the radiographic method is dependent on a 2D coordinate system that by definition cannot simulate the sagittal plane required to calculate the angle of version (Murray 1993). EBRA offers the advantage of using complex geometric calculations to simulate the 3D position of the acetabular

DOI 10.3109/17453674.2015.1017791

cup. In 3D-CT, variations in pelvic tilt can be controlled by fixing the pelvis to a standardized frame of reference, such as the anterior pelvic plane (APP). Given the disadvantages of greater radiation exposure, it is not known if 3D-CT is any more accurate than the EBRA method of cup analysis in MoM HA.

The null hypothesis of this study was that there was no difference in measurements of cup version and inclination between 2D and 3D imaging. The primary aim was therefore to quantify the agreement in measurements of cup version of large-diameter MoM hips using EBRA and 3D-CT. The secondary aim was to quantify the agreement between measurements of cup inclination. The last aim was to determine the inter- and intra-observer reliability of both methods.

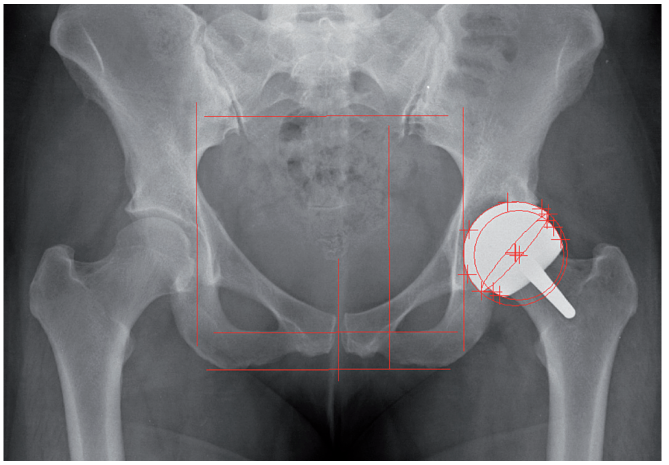

Figure 1. EBRA analysis with a left MoM hip resurfacing arthroplasty in situ. A frontal plane is developed, as represented by the central red square. The cup dome (best-fit circle shown in red) and rim (best-fit ellipse shown in red) are marked out by the user in order to calculate inclination and version.

Patients and methods

We retrospectively retrieved the AP pelvic and lateral hip radiographs, as well as low radiation pelvis CT scans, of 100 consecutive patients who had attended our dedicated metal-on-metal hip research clinics between 2009 and 2010. These imaging procedures were carried out within 6 weeks of each other. 87 hips were analyzed in a sample consisting of 81 patients (mean age 56 (26–74) years, 55 men), each with a current-generation large-diameter MoM HA (84 hip resurfacings and 3 modular total hips in total). Radiographs of 19 patients were excluded, as the entire pelvis had not been captured on the conventional radiographs. The sizes of the femoral and acetabular components used were retrieved from the operation records.

2D radiographic analysis

Digital supine pelvic radiographs were taken in standardized fashion with the anterior superior iliac spines (ASISs) included, a symmetrical appearance of both oburator foramen, and the coccyx appearing directly in line with the pubic symphysis (Tannast et al. 2005a). The X-ray beam was centered on the midline and directed at the pubic symphysis.

Analysis of cup orientation was conducted by importing the radiograph into EBRA software. The image was first calibrated to the specific head and cup size. 6 grid lines (3 vertical and 3 horizontal) were generated by marking specific bone landmarks on the pelvis. The cup dome was marked with 4 points. In addition, the rim was delineated either by marking 3 specific points (the supero-lateral apex, the infero-medial apex, and an arbitrary point) or a minimum of 5 evenly distributed points along the anterior or posterior outline of the rim (Figure 1). From these points, a best-fit ellipse representing the rim of the cup was created. Lateral radiographs were used to determine anteversion or retroversion (Grammatopoulos et al. 2010, Langton et al. 2010b).

The software calculates inclination in the plane of the radiograph, as the angle between the EBRA base line (double tangent to the oburator foramina) and the longer axis of symmetry of the ellipse. Version is defined as the slope angle of the cup axis with respect to the film plane.

3D-CT analysis

All postoperative CT scans (Somatom Sensation 64-bit; Siemens, Erlangen, Germany) were performed with an extended Hounsfield range of 16,000 units using a low-dose CT protocol with 0.75-mm collimation, allowing clear imaging of the implanted components with minimal metal artifact. The data was reformatted to 3D models and analyzed using commercially available software (Robin's 3D; Robin Richards, London, UK; www.robins3D.co.uk) (Henckel et al. 2006, Dandachli et al. 2008, 2009). In each case, the cup orientation was first measured in the frame of reference of the CT scanner, and then in the anterior pelvic plane (APP) developed from the anterior-most prominence of the ASISs and pubic tubercles. From this, transverse, coronal, and parasagittal planes were established. Using simultaneous coronal, sagittal, and axial views, a plane across the cup face was produced by setting points along the rim of the acetabular component (Figure 2). The acetabular cup axis was defined by a vector passing through the center of the cup and perpendicular to the cup face. Radiological inclination and version were calculated by the software based on the nomograms and equations given by Murray (1993).

Measurements were conducted by KD and NS, who had already used EBRA and 3D-CT in over 50 cases before this study. For tests of reliability, 30 randomly selected hips were measured in random order by these observers using both imaging modalities, 3 times at 2-weekly intervals. The observers were blinded regarding any patient identifiers.

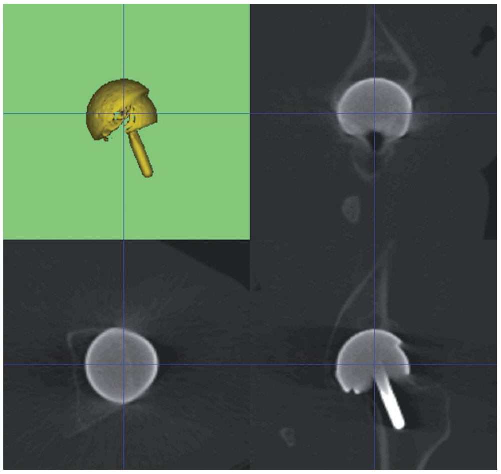

Figure 2. Simultaneous coronal, sagittal, and axial views of an acetabular component. The outline of the acetabular component is marked using simultaneous coronal, sagittal, and axial views.

Statistics

To quantify the level of agreement for radiographic angles of cup version and inclination, a Bland-Altman analysis (Bland and Altman 1986) was carried out comparing EBRA values with 3D-CT values. To demonstrate the clinical significance of the 2 imaging methods, a scatter graph was created where each plot represented the inclination (x-axis) and version (y-axis) of each hip measured (Figures 3–5). The number of hips within a range of 35° to 55° inclination and 10° to 30° version was determined, converted to dichotomous data, and compared by Fisher's exact test. These specific values were selected as being representative of what is considered a safe-zone target for MoM cup placement (Grammatopoulos et al. 2010). Any p-value of < 0.05 was considered statistically significant. Data were analyzed using SPSS software for Windows version 20.

To quantify the inter- and intra-observer reliability of our measurements, the intra-class coefficient (ICC) was calculated. This measures repeatability and reproducibility between pairs of observations, whereby an ICC of "1" indicates perfect agreement, while "0" indicates no agreement (Walter et al. 1998). Based on previously published work examining similar criteria, a power analysis determined that a sample size of 30 hips would be sufficient for an α-error of 0.05 and β-error of 0.20. The ICC of the 3 observations was calculated to describe the intra-observer reliability. Inter-observer reliability was calculated by comparing the mean of the 3 observations of the first author (KD) with those of the second (NS).

Ethics

All patients had consented for their imaging to be used for research purposes. The use of CT was approved by the local ethics review committee (REC reference 07/Q0401/25, approval date August 13, 2007).

Results

Bland-Altman analysis showed a mean difference of 6° in version between EBRA and 3D-CT with the pelvis supine, and 8° with the pelvis orientated to the APP. The 2-standard deviation (2-SD) limits of agreement were wide at 8° to –20° and 6° to –22°, respectively. The mean difference in cup inclination was 1° when EBRA was compared to 3D-CT with the pelvis supine, and 0° with the pelvis adjusted to the APP. The 2-SD limits of agreement were wide at 9° to –7° and 6° to –6°, respectively.

Safe zone analysis

When cup inclination and version were plotted on scatter graphs, 53% of the hips were within the 20° safe zone when measured by 3D-CT with pelvis supine and 54% when measured with the pelvis adjusted to the APP (Figures 3 and 4).

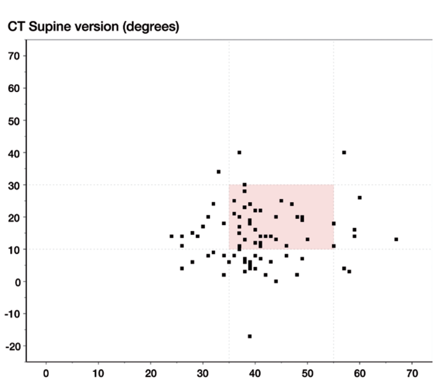

Figure 3. Scatter plot of cup inclination (x-axis) against cup version (y-axis) measured using 3D-CT with the pelvis in the supine position. The red square shows a notional safe zone with ±10° from 45° inclination and 20° anteversion.

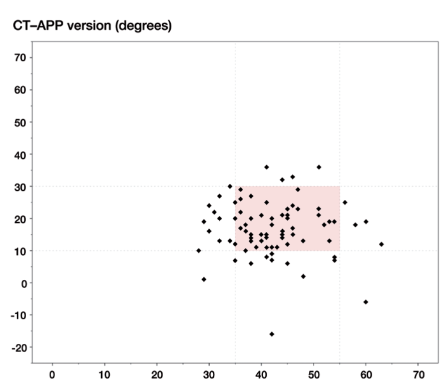

Figure 4. Scatter plot of cup inclination against cup version measured using 3D-CT with the pelvis in the APP position.

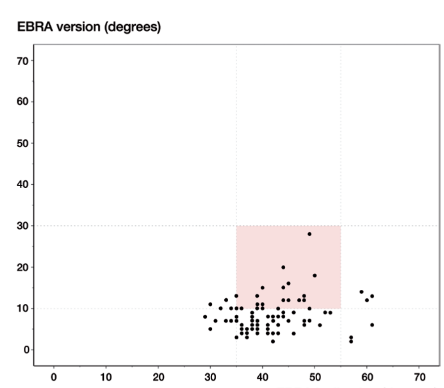

Figure 5.Scatter plot of cup inclination against cup version measured using EBRA software.

Table 1. Safe-zone analysis of cups measured using EBRA and 3D-CT

	Within safe zone	Outside of safe zone	p-value [a]
EBRA	21	66	
CT supine	46	41	< 0.001
CT APP	47	40	< 0.001

[a] Fisher's exact test

Table 2. Intra- and inter-observer reliability for cup orientation measurements using EBRA and 3D-CT

	Intra-class coefficient (95% CI) Intra-observer reliability	Inter-observer reliability
EBRA, version	0.89 (0.76–0.96)	0.79 (0.51–0.90)
3D-CT, version	0.99 (0.99–1.0)	0.98 (0.96–0.99)
EBRA, inclination	0.99 (0.99–1.0)	0.97 (0.94–0.99)
3D-CT, inclination	0.99 (0.99–1.0)	0.99 (0.98–1.0)

This proportion was 24% when measured by EBRA (Figure 5). The difference was statistically significant (Table 1).

Observer reliability

Although EBRA measurements of version showed good intra-observer reliability (ICC = 0.89, 95% CI: 0.76–0.96), those from 3D-CT of version were near-perfect (ICC = 0.99) with a narrower 95% CI (0.99–1.0). EBRA and 3D-CT measurements of inclination both demonstrated excellent intra-observer reliability (ICC = 0.99, 95% CI: 0.99–1.0).

In testing inter-observer reliability, 3D-CT gave better (i.e. near-perfect) agreement in version values than EBRA (ICC = 0.98 vs. 0.79), with a narrower 95% CI (0.96–0.99 vs. 0.51–0.90). The reliability of inclination values was also high, whether measured by EBRA or by 3D-CT (0.99 vs. 0.97) (Table 2).

Discussion

We found that EBRA measurements of cup orientation, particularly version, have poor agreement and are less reliable than those from 3D-CT. The differences between the 2 modalities may be sufficiently great to affect the validity of conclusions based on 2D measurements. The influence of cup version and inclination on MoM bearing failure has been mainly investigated using 2D analysis of conventional radiographs with EBRA software (Langton et al. 2008, 2009, Grammatopoulos et al. 2010, Langton et al. 2010a, Bolland et al. 2011, Langton et al. 2011). These studies represent the greatest body of work in the literature and include over 4,000 MoM hips. The difference in orientation values between 2D measurements with EBRA and 3D-CT has not been established, and the present study appears to be the only one to have been conducted.

Version

Our results suggest that using EBRA is inaccurate and tends to underestimate cup version. So a cup will appear more retroverted if measured with EBRA than if measured using 3D-CT. Our EBRA measurements were highly reliable, suggesting that the poor agreement with 3D-CT is attributable to the method of measurement rather than to the learning curve of the observers in this study. The version value calculated by EBRA is a function of the ability of the user to accurately mark the contour of the cup, for the cup axis to be generated from a best-fit ellipse. The anterior and posterior cup rim are often obscured by a large metal femoral head (Hart et al. 2009), which is of similar radio-opacity, making the central portion of the rim difficult to visualize. This may have contributed to the relatively poor inter- and intra-observer reliability that we found in this study. Where the rim of the cup is more easily identified, such as in polyethylene cups for total hip arthroplasty, EBRA has greater accuracy (Biedermann et al. 2005). By comparison, 3D-CT enables the user not only to generate an axial and sagittal plane but also to visualize the entire circumference of the cup when an extended Hounsfield scale is used to minimize metal artifact. Both are likely to contribute to better accuracy and reproducibility, reflected in the near-perfect intra- and inter-observer reliability.

There were 3 hips in which retroversion was evident on 3D-CT but not on EBRA. Lateral radiographs were assessed according to the method reported by Grammatopolous et al. (2010), but retroversion could not be detected according to their criteria. These findings reflect those of Langton et al. (2010b) in the only study in the literature to validate EBRA in MoM hips using a controlled laboratory setting. 50 radiographs of current-generation metal cups were mounted in a synthetic pelvis without a femoral head in situ, to a predetermined orientation. Only 1 of several cups placed in a retroverted position was identified by EBRA. This result was excluded from the validation analysis, and is a limitation of the software acknowledged by the authors. This is clinically relevant, as a recent study found that 10 of 100 MoM hips were retroverted on 3D-CT analysis (Hart et al. 2011).

Inclination

The error between inclination values for the 2 techniques was substantially less when compared to version, probably because the superior and inferior margins of the cup are readily identified on conventional radiographs, even with large-diameter metal heads. The discrepancy is probably related to the disadvantages of 2D measurement (rather than 3D measurement) (Kalteis et al. 2006). The radiographic plane from which inclination is calculated is prone to errors from variations in pelvic tilt, rotation, and obliquity that occur not only between subjects but also when the same subject is serially assessed

(Nishihara et al. 2003, Tannast et al. 2005a, Ghelman et al. 2009, Kalteis et al. 2009). A critical advantage of 3D-CT is that the pelvis is corrected to the APP, eliminating the variability in patient positioning at the time of scanning, thus allowing objective measurements of cup placement to be made between different subjects.

"Safe-zone" scatter graphs

Safe-zone graphs have been popularized in the hip arthroplasty literature since the time of Lewinnek et al. (1978), to determine surgical accuracy and examine problems associated with a particular device. In our analysis, the difference in the number of hips falling within the safe zone was substantial. This may have implications for any study using the EBRA method to investigate outcomes related to malorientation of MoM HA cups. The incidence of complications, such as pseudotumor, as well as an individual's surgical performance may be under- or over-reported depending on whether EBRA or 3D-CT orientation values are used to plot safe-zone graphs.

Limitations of the study

The present study had several limitations, in part due to its retrospective nature. Firstly, supine pelvic radiographs were used, in contrast to a large number of MoM studies that used the standing position. There is substantial variability in pelvic orientation in both the supine and the standing position when measured in the same patient over time. The appearance of the pelvis and an acetabular component can therefore be inconsistent on successive radiographs. Standing films are thus no more accurate for the purpose of determining cup orientation than films with the pelvis in the supine position, as neither can be truly standardized (Nishihara et al. 2003, DiGioia et al. 2006, Beckmann et al. 2009, Wan et al. 2009). Using 3D imaging, the pelvic tilt can be fixed to standardize reference plane such as the APP, allowing us to overcome this issue.

Secondly, we assumed that there had not been a substantial change in the pelvic tilt or cup position in the time interval between the radiograph and CT scan being taken. It would have been ideal to perform both investigations sequentially on the same day, but this was not possible logistically in a busy urban hospital. Indeed, an improvement to our study design would be to perform a controlled laboratory-based investigation. Cup position could be set within a synthetic pelvis to a series of known orientations to a standardized pelvic position and measured with both EBRA and 3D-CT. This could be performed with a metal femoral head in situ, to give a better representation of the clinical setting.

Thirdly, different acetabular components with variable cup articular arc angles (CAAA) were studied. De Haan et al. (2008), Langton et al. (2008), and Ghelman et al. (2009) demonstrated the importance of the functional articular arc as it relates to wear complications with large-diameter MoM hips. The amount of articular arc available is a function not only of the size, but also of the inclination angle of the cup. Studies seeking to quantify the performance of a specific cup design with regard to its CAAA must therefore rely on robust measurements of cup orientation.

Fourthly, the manufacturers of EBRA recommend that the accuracy of the software may be improved by measuring cup orientation on sequential radiographs and calculating an average of both version and inclination. Given the retrospective nature of this study, this would not have been possible.

Lastly, there may be concerns regarding the radiation dosage of CT. The scanning protocol at our institution is specifically designed to reduce the radiation exposure to 1.7 mSv, which is much less than the 10 mSv for a traditional pelvic CT. The dose is the equivalent of 3 pelvic radiographs (Oatway and Hughes 2005). The dose for a single pelvic radiograph required for EBRA analysis is 0.5 mSV. However, with current guidelines recommending long-term clinical surveillance of MoM hips, the radiation exposure from a single low-dose CT scan is likely to be matched by that of the successive radiographs a patient will require for EBRA measurements.

Understanding the effect of cup orientation on outcome and modes of failure in MoM arthroplasty is dependent on an objective tool that allows the user to accurately and reliably measure these values regardless of pelvic position at the time of radiographic exposure. We have shown a large, and clinically relevant, difference in cup version values when using 3D-CT. Surgeons and researchers should be aware of these differences when interpreting the orientation of MoM cups measured with the EBRA 2D technique.

KD was the principal investigator and was assisted by NS in the observer reliability tests. JC and AH were responsible for overseeing the study and for editing the final manuscript. All the authors approved the final manuscript.

No competing interests declared.

Biedermann R, Tonin A, Krismer M, Rachbauer F, Eibl G, Stockl B. Reducing the risk of dislocation after total hip arthroplasty: the effect of orientation of the acetabular component. J Bone Joint Surg Br 2005; 87(6): 762-9.

Bland J M, Altman D G. Statistical methods for assessing agreement between 2 methods of clinical measurement. Lancet 1986; 1(8476):307-10.

Bolland B J, Culliford D J, Langton D J, Millington J P, Arden N K, Latham J M. High failure rates with a large-diameter hybrid metal-on-metal total hip replacement: clinical, radiological and retrieval analysis. J Bone Joint Surg Br 2011; 93(5): 608-15.

Dandachli W, Kannan V, Richards R, Shah Z, Hall-Craggs M, Witt J. Analysis of cover of the femoral head in normal and dysplastic hips: new CT-based technique. J Bone Joint Surg Br 2008; 90(11): 1428-34.

Dandachli W, Islam S U, Liu M, Richards R, Hall-Craggs M, Witt J. Three-dimensional CT analysis to determine acetabular retroversion and the implications for the management of femoro-acetabular impingement. J Bone Joint Surg Br 2009; 91(8): 1031-6.

Dandachli W, Ul Islam S, Tippett R, Hall-Craggs M A, Witt J D. Analysis of acetabular version in the native hip: comparison between 2D axial CT and 3D CT measurements. Skeletal Radiol 2011; 40(7): 877-83.

DiGioia A M, Hafez M A, Jaramaz B, Levison T J, Moody J E. Functional pelvic orientation measured from lateral standing and sitting radiographs. Clin Orthop Relat Res 2006; 453: 272-6.

Ghelman B, Kepler CK, Lyman S, Della Valle AG. CT outperforms radiography for determination of acetabular cup version after THA. Clin Orthop Relat Res 2009; 467(9): 2362-70.

Grammatopoulos G, Pandit H, Glyn-Jones S, McLardy-Smith P, Gundle R, Whitwell D, et al. Optimal acetabular orientation for hip resurfacing. J Bone Joint Surg Br 2010; 92(8): 1072-8.

Hart A J, Dandachli W, Schlueter-Brust K, Henckel J, Cobb J. Large ball metal on metal hips obscure cup angle measurement on conventional radiographs. Hip Int 2009; 19(4):323-9.

Hart A J, Skinner J A, Henckel J, Sampson B, Gordon F. Insufficient acetabular version increases blood metal ion levels after metal-on-metal hip resurfacing. Clin Orthop Relat Res 2011; 469(9): 2590-7

Henckel J, Richards R, Lozhkin K, Harris S, Baena F M, Barrett A R, et al. Very low-dose computed tomography for planning and outcome measurement in knee replacement. The imperial knee protocol. J Bone Joint Surg Br 2006; 88(11): 1513-8.

Ilchmann T, Mjoberg B, Wingstrand H. Measurement accuracy in acetabular cup wear. Three retrospective methods compared with Roentgen stereophotogrammetry. J Arthroplasty 1995; 10(5): 636-42.

Kalteis T, Handel M, Herold T, Perlick L, Paetzel C, Grifka J. Position of the acetabular cup -- accuracy of radiographic calculation compared to CT-based measurement. Eur J Radiol 2006; 58(2): 294-300.

Kalteis T A, Handel M, Herbst B, Grifka J, Renkawitz T. In vitro investigation of the influence of pelvic tilt on acetabular cup alignment. J Arthroplasty 2009; 24(1): 152-7.

Langton D J, Jameson S S, Joyce T J, Webb J, Nargol AV . The effect of component size and orientation on the concentrations of metal ions after resurfacing arthroplasty of the hip. J Bone Joint Surg Br 2008; 90(9): 1143-51.

Langton DJ , Sprowson A P, Joyce T J, Reed M, Carluke I, Partington P, et al. Blood metal ion concentrations after hip resurfacing arthroplasty: a comparative study of articular surface replacement and Birmingham Hip Resurfacing arthroplasties. J Bone Joint Surg Br 2009; 91(10): 1287-95.

Langton D J, Jameson S S, Joyce T J, Hallab N J, Natu S, Nargol A V. Early failure of metal-on-metal bearings in hip resurfacing and large-diameter total hip replacement: A consequence of excess wear. J Bone Joint Surg Br 2010a; 92(1): 38-46.

Langton D J, Sprowson A P, Mahadeva D, Bhatnagar S, Holland J P, Nargol A V. Cup anteversion in hip resurfacing: validation of EBRA and the presentation of a simple clinical grading system. J Arthroplasty 2010b; 25(4): 607-13.

Langton D J, Joyce T J, Jameson S S, Lord J, Van Orsouw M, Holland J P, et al. Adverse reaction to metal debris following hip resurfacing: the influence of component type, orientation and volumetric wear. J Bone Joint Surg Br 2011; 93(2): 164-71.

Lewinnek G E, Lewis J L, Tarr R, Compere C L, Zimmerman J R. Dislocations after total hip-replacement arthroplasties. J Bone Joint Surg Am 1978; 60(2): 217-20.

Murray D W. The definition and measurement of acetabular orientation. J Bone Joint Surg Br 1993; 75(2): 228-32.

Nishihara S, Sugano N, Nishii T, Ohzono K, Yoshikawa H. Measurements of pelvic flexion angle using three-dimensional computed tomography. Clin Orthop Relat Res 2003; 411: 140-51.

Oatway W, Hughes S. National Dose Assessment Working Group Paper 7.02: localised charts to show doses by county. 2005. http://www.ndawg.org/documents/Paper7.02.pdf.

Phillips N J, Stockley I, Wilkinson J M. Direct plain radiographic methods versus EBRA-Digital for measuring implant migration after total hip arthroplasty. J Arthroplasty 2002; 17(7): 917-25.

Tannast M, Langlotz U, Siebenrock K A, Wiese M, Bernsmann K, Langlotz F. Anatomic referencing of cup orientation in total hip arthroplasty. Clin Orthop Relat Res 2005a; 436: 144-50.

Tannast M, Zheng G, Anderegg C, Burckhardt K, Langlotz F, Ganz R, et al. Tilt and rotation correction of acetabular version on pelvic radiographs. Clin Orthop Relat Res 2005b; 438: 182-90.

Walter S D, Eliasziw M, Donner A. Sample size and optimal designs for reliability studies. Stat Med 1998; 17(1):101-10.

Wan Z, Malik A, Jaramaz B, Chao L, Dorr L D. Imaging and navigation measurement of acetabular component position in THA. Clin Orthop Relat Res 2009; 467: 32-42.