Clinical Comparison of Polyethylene Wear with Zirconia or Cobalt-Chromium Femoral Heads

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Abstract Ceramic femoral heads were developed to reduce the wear of conventional ultrahigh-molecular-weight polyethylene (UHMWPE) bearing surfaces in THA. We compared the wear rates of PE acetabular components bearing against femoral heads of zirconia (Zr) or cobalt-chromium (CoCr) in young patients. One surgeon inserted CoCr femoral heads in all 33 patients (33 hips) having THA for primary osteoarthritis from 1996 to 1997 and then Zr femoral heads in all 34 patients (36 hips) from 1998 to 1999. The mean age of the entire cohort was 52.5 years (range, 29–64 years). The shells were solid and hydroxyapatite (HA) -coated, liners were argon-sterilized UHMWPE, and head size was 28 mm. The minimum clinical followup was 56 months (mean, 65 months; range, 56–77 months); minimum 5-year radiographs were available for 62 of the 68 patients. Wear analysis of digitized anteroposterior (AP) radiographs was performed with a computerized method. Demographic data were comparable in the two groups.

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Each author certifies that his or her institution either has waived or does not require approval for the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

This work was performed at Aarhus University Hospital.

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Mean femoral head penetration rate was similar in the two types of heads (CoCr: 0.25 mm/year; range, 0.21–0.33 mm/year; Zr: 0.23 mm/year; range, 0.20–0.29 mm/year), as was mean linear wear (CoCr: 1.22 mm; range, 0.28–3.78 mm; Zr: 1.11 mm; range, 0.15–2.05 mm). There were no revisions. These data support skepticism regarding the clinical wear advantage of Zr compared with CoCr femoral heads. The explanation for the clinical similarity of wear, despite the theoretical advantages of ceramic heads, needs further investigation.

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

Introduction

PE wear leading to osteolysis and aseptic loosening is considered by some to be the major factor limiting the longevity of THAs [4, 9, 31, 32]. Many attempts have been made to improve the success of THA, including enhancement of design, surface coating, cements, and articulating bearings.

Zr femoral heads were introduced in 1985 to solve the problems of alumina head fracture and lessen the concern of PE wear debris. Several laboratory studies suggest an advantage of ceramic over metal heads [6, 10, 24, 29], predicting 22% to 77% reduction of PE wear with Zr femoral heads dependent on the head size [12]. One survey of 19 articles [28] suggests clinical wear studies have not shown a similar advantageous wear profile for Zr heads, but rather are contradictory and report wide variations in magnitude of wear (eg, from less than 0.1 mm/year to greater than 0.5 mm/year). Hernigou and Bahrami [17] and von Schewelov et al. [35] showed a higher wear rate of

PE with Zr than with metal heads. However, Kim [20] reported wear rates in favor of Zr heads. Also, the studies report varying head sizes, types of PE, and methods used to measure PE wear, which make comparisons difficult (Table 1).

Based on laboratory predictions, we hypothesized midterm (minimum 5 years) wear of the PE in the patient group with CoCr femoral heads would increase compared with Zr femoral heads when head size was kept constant.

Materials and Methods

We retrospectively compared the wear in all 67 patients (69 hips) younger than 65 years having THA for primary or secondary osteoarthritis from 1996 to 1999. From 1996 to 1997, CoCr femoral heads were used in all 33 patients (33 hips), and from 1998 to 1999, Zr femoral heads were used in all 34 patients (36 hips). Early (mean, 3.7 years) true wear rates (eliminating creep) greater than 0.1 mm/year are strongly associated with later osteolysis [15]. A preliminary power analysis based on long-term (12 years) PE wear data of a similar study (mean, 0.134 mm/year; standard deviation [SD], 0.14 mm/year) [17] and targeting a mean difference in PE wear rate of 0.1 mm/year suggested 31 patients per group with a power of 80% ($\alpha = 0.05$). The minimum clinical followup was 56 months (mean, 65 months; range, 56–77 months). Five-year radiographs were missing for six of the 67 patients (9%) and we used the latest radiographs (24–37 months) to measure wear in these cases. We observed no differences between the two groups with respect to age, gender, weight, hip side, cup size, followup duration, distribution of PE liner thicknesses, or Harris hip score (HHS) (Table 2).

The THA was a so-called hybrid with a cemented femoral component and an uncemented acetabular component. All operations were performed by one orthopaedic consultant (KAN) using the posterolateral approach. We attempted to restore leg length and lateral offset. The acetabular components were all uncemented, titanium (Ti) plasma-sprayed, and HA-coated and of the same design (Mallory-Head, Solid Finned Ringloc[®] metal shells; Biomet Inc, Warsaw, IN). They were inserted using the same technique (approximately 2-mm press-fit by coating thickness, line-to-line reaming). In all cases, the PE liners were a compression-molded, UHMWPE resin, consolidated, packed, and sterilized by gamma irradiation in argon gas in the range of 2.5 to 4 Mrad (ArCom[®]; Biomet Inc). All femoral components were of the same design (Exeter[®]; Stryker, Kalamazoo, MI) and inserted using the same technique, including distal plugging, pulsatile lavage of the medullary canal, and pressurized injection of vacuum-

Table 1. Summary of clinical publications with 28-mm femoral heads

Study	Design	Mean followup (years)	Mean patient age (years)	Time of surgery	Method	Linear wear rate (mm/year)	
						Zirconia heads	Metal heads
Hemigou and Bahrami [17]	Comparative	5	69	1988–1990	Modified PolyWare	0.043 (n = 40)	0.036 (n = 20)
Hemigou and Bahrami [17]	Comparative	12	69	1988–1990	Modified PolyWare	0.412 (n = 40)*	0.134 (n = 20)
Kim [20]	RCT, bilateral	7.1 (5–8)	44	1996–1999	AutoCAD	0.08 (n = 52)*	0.17 (n = 52)
Kraay et al. [23]	RCT	4.3	69	Before 2001	Hip Analysis Suite	0.06 (n = 27)	0.055 (n = 30)
Allain et al. [1]	Patient series	5.8 (1–9)	56	1988–1991	Livermore	0.09 (n = 78)	
Kim and Kim [21]	Retrieval, compared to Al	9.8 (7.5–15)	48	?	AutoCAD	0.09 (n = 24)	
Cohn et al. [7]	Comparative	4.0 (2–9.1)	< 70	1998–2005	Hip Analysis Suite	0.14 (n = 36)	0.11 (n = 22)
Current study	Comparative	5 (2–6.4)	52.5	1996–1999	PolyWare	0.23 (n = 36)	0.25 (n = 33)

* Statistically significant difference; RCT = randomized clinical trial.

Table 2. Patient demographics

Input variable	Zirconia heads	Cobalt-chromium heads
Number of hips	36	33
Gender (male/female)	22/14	19/14
Side (right/left)	18/18	19/14
Mean age at operation (years)	53.5 (43–64)	51.5 (29–60)
Mean cup size (mm)	56.5 (50–62)	60 (50–62)
Mean liner thickness (mm)	9.38 (6.8–11.8)	9.25 (6.8–11.8)
Mean weight (kg)	79 (58–112)	77 (55–120)
Mean radiographic followup (months)	58 (24–77)	58 (37–72)
Mean preoperative Harris hip score (maximum, 100 points)	54	57
Mean Harris hip score 3 months postoperatively (maximum, 100 points)	88	92

mixed Simplex[®] P polymethylmethacrylate bone cement (Stryker Howmedica, Rutherford, NJ). All femoral heads were 28 mm. The femoral heads inserted during 1996 and 1997 were CoCr heads (Howmedica Osteonics Corp, Allendale, NJ), and the femoral heads inserted during 1998 and 1999 were yttria-stabilized Zr ceramic (Prozyr[®]) produced by St Gobain-Desmarquest Céramiques (Evreux, France) by sintering and hot isostatically pressing.

Postoperatively, we mobilized patients on the day after surgery with weightbearing as tolerated. Walking was assisted by crutches for as long as needed (typically 6 weeks; maximum, 12 weeks) and full weightbearing was allowed. During their hospital stay (4–6 days), patients received daily supervised physiotherapy focused on daily activities of living (ie, dressing, bathing, and getting in and out of bed).

One of us (KAN) determined the HHS before surgery and 3 months after surgery. After the final followup of all patients, we checked the patient records and the Danish Hip Arthroplasty Registry, a nationwide clinical database on primary THAs, revisions, and postoperative complications in patients in Denmark since the beginning of 1995, for cases of revision and/or complications. No patients were lost to clinical followup at 5 years.

We routinely evaluated each patient radiographically at six approximate times: immediately postoperative, 3 months, 6 months, 1 year, 2 years, and 5 years. At each radiographic evaluation, the patient had a nonweightbearing AP and crosstable lateral radiograph of the hip. We used four radiographs per patient to determine the total amount of wear in intervals. We selected the 3-month postoperative radiographs as baseline (Time 0), as these images were of better quality than the immediately postoperative images. In addition, we analyzed the 1-year, 2-year, and 5-year followup radiographs. The radiographs also were evaluated for aseptic loosening (progressive radiolucent lines along the implant edges) and osteolysis (periprosthetic bone resorption with radiographic evidence

of progressive bone loss not present on the initial radiographs) [36]. The location of osteolytic lesions was described according to the three zones defined by DeLee and Charnley [11], and its area was measured digitally and expressed in mm².

We performed radiographic measurements of two-dimensional femoral head penetration into the PE with a computerized method (PolyWare 5.10 Digital version; Draftware Developers Inc, Vevay, IN) validated for clinical measurement [14, 18] of PE wear in metal-backed acetabular components [13]. The method uses a digital detection algorithm to fit circles to the peripheries of the femoral head and acetabular cup and relies on computer-assisted technology to place a three-dimensional solid model of the acetabular component and femoral head on the basis of back-projection (shadow-casting) of the radiographs and computer-assisted design knowledge of the implant (Fig. 1) [8]. Linear wear was measured in the plane of the AP radiograph by the software with an accuracy of approximately 0.15 mm [13]. Based on previously published practice [8, 23] and our experience with the problems of poor-quality lateral radiographs, we decided to include only the AP radiographs in the analysis. Therefore, the results reported in this study are two-dimensional linear head penetration rates. Radiographs were digitized to 300 dpi at 100% scale in a high-resolution optical scanner (Mustek P3600 A3 Pro; Mustek, Irvine, CA). The 5-year radiographs were missing for two patients with CoCr heads and four with Zr heads, but they were included in the analysis to the available 2-year followup. Five patients with CoCr heads and one patient with a Zr head had their 5-year radiographs some months before the exact date for 5-year followup owing to work abroad or surgery/radiographic control of the contralateral hip; these were considered to be 5-year radiographic followups. One patient by error had a 30-mm Zr head inserted at surgery but underwent immediate reoperation with a head (28-mm) and liner exchange, as it was evident on the postoperative radiograph that the

Fig. 1A–B The computerized measurement of wear with PolyWare 5.10 is shown. (A) Circles are fit to the peripheries of the femoral head and the acetabulum, (B) a three-dimensional solid model is created, and the vector distances between the cup and the head centers on followup radiographs are calculated.

femoral head was not correctly centralized in the cup. Because we used the 3-month radiographs as baseline, this patient was included in the wear analysis. One patient with a Zr femoral head, additional to the total number of 34 patients with Zr femoral heads, was excluded because we lacked the cup size and all radiographs after 3 months of followup. The number of hips available for analysis of PE wear therefore was 33 patients (33 hips) with CoCr femoral heads and 34 patients (36 hips) with Zr femoral heads. The quality of the digitized AP radiographs generally was good and the automatic circle fitting only rarely had to be overruled by the manual digitizer tablet. In the few radiographs (one CoCr, seven Zr) in which manual overrule was necessary, five evenly spaced points were systematically placed along the implant borders in the radiograph. PE wear analysis was performed in four intervals between the five followups (3 months, 6 months, 1 year, 2 years, and 5 years) by one experienced observer (CS) (Fig. 2). The observer (CS) was blinded to the groups. Quantitative assessment of femoral head penetration was performed twice on 15 random patients by the observer (CS) 1 month apart, and the mean absolute difference between the first and second analyses was 0.04 mm (SD, 0.43 mm; range, 0–0.22 mm). Followup from the day of surgery to the final radiographic followup was rounded to whole months by ± 15 days in calculation of the annual wear rate.

According to a Shapiro-Wilk test [2], the mean annual femoral head penetration rates were normally distributed when converted to log scale. Similarity or difference in variances of the log scale penetration rates for the two groups was tested by an F test. The log mean values of the two groups were compared by a two-sample t test with equal variances (wear rates). With the linear wear data, normality could not be achieved by transforming the data (log scale and cubic transformation) and thus they were tested by a nonparametric test (Mann-Whitney U test). Linear wear (mm) of the longest followup per patient (minimum, 2 years; maximum,

Fig. 2 Linear PE wear (head penetration into the PE liner) was similar with Zr-on-PE and CoCr-on-PE during the 5 years of followup. The wear rates were progressive throughout the entire followup, but a steady-state level was reached after 2 years.

6.4 years) and wear rates (mm/year) are presented on a normal scale for interpretational reasons. Continuous demographic input variables between the groups were compared by a two-sample t test with equal variances, and categorical variables were tested by a chi square test, although cells with observations of five or less were tested by Fisher's exact test. Differences in improved HHS (preoperative versus 3 months postoperative) between the groups were tested nonparametrically (Mann-Whitney U test). The Intercooled Stata[®] 10.0 (StataCorp LP, College Station, TX) package was used for statistical computations.

Results

There was no difference ($p = 0.73$) between the mean annual femoral head penetration rate for the CoCr group ($n = 33$; 0.25 mm/year; SD, 0.16 mm/year; range, 0.05–

0.81 mm/year) and the Zr group ($n = 36$; 0.23 mm/year; SD, 0.12 mm/year; range, 0.07–0.66 mm/year). Reflected by variance, the distribution of wear was similar ($p = 0.46$) between the groups. Fifty-eight percent of the Zr heads had a wear rate greater than 0.2 mm/year compared with 51% of the CoCr heads. Mean linear wear at 5 years was similar ($p = 0.80$) in the Zr group (1.11 mm; SD, 0.53 mm; range, 0.15–2.05 mm) compared with the CoCr group (1.22 mm; SD, 0.74 mm; range, 0.28–3.78 mm) (Fig. 2).

There was no difference ($p = 0.25$) between the two groups in the improvement of HHS comparing the score obtained before surgery with the 3-month postoperative score.

Complications in the CoCr group consisted of two femur fractures at 7 months and 3 years postsurgery, but no component revisions were performed and the patients were included for wear measurements after the fractures because they returned to their habitual functional level after recovery. Two patients had one episode of early posterior hip dislocation and were treated with closed reduction. There were no postoperative infections in either group. There were no revisions in any of the patients within the 5-year followup period. Radiographic evaluation of all last-examination AP radiographs revealed no sign of aseptic loosening (progressive radiolucent lines) of any acetabular or femoral components. Only one patient in the CoCr group had an evident DeLee and Charnley Type 3 acetabular osteolysis of 22.4 mm² seen on the conventional radiographs at the 5-year followup.

Discussion

Zr has good biocompatibility, and mechanical and sliding characteristics [5, 24, 29]. Despite this, several clinical studies have reported a higher annual wear rate of Zr-on-UHMWPE than expected based on laboratory studies [17, 23, 35]. Clinical publications with components similar to those addressed in our study are few and have conflicting results (Table 1), and only one author [20] reported a superior clinical wear performance with Zr over metal heads. We therefore hypothesized there would be increased midterm wear in the patient group with CoCr femoral heads compared with Zr femoral heads when head size was kept constant.

There are several limitations to our study. Although no patients were lost to followup, missing radiographs deprived us of the option of midterm (ie, minimum of 60 months) wear analysis for six patients (followup, 24–37 months). This potentially could have introduced selection bias. However, none of these patients had revision surgery, and according to their 5-year clinical followup, they had returned to work shortly after surgery and still were working and doing well. Therefore, we do not believe

the lack of a minimum 5-year image with this relatively small number of patients would substantially influence our conclusions. The patients were not randomized, but the potentially confounding variables we assessed were similar (Table 2). Even when controlled for other factors, PE wear is greater in males than in females [32]. Thus, the smaller proportion of females in both groups might have biased the wear rates accordingly. The activity level of this young patient group could not be controlled for and may have had a substantial influence on the overall measured femoral head penetration. The computerized wear measurement techniques available for plain radiographs [8] of AP hips have limited accuracy with low-wear detections in the clinical setting and variation in the cup position and cross-stable lateral images [8, 16]. However, computerized techniques are considerably more accurate and reproducible than manual methods, and the method used in this study has been validated for studies of longer-term followup and/or high wear [18]. We used only AP images, and despite the fact that the radiographs were digitized hard copies, the quality was good. The density of Zr is less than that of CoCr, which potentially could cause difficulties in outlining the femoral head contour, but automatic detection of the femoral head was successful in 98% of the images.

HA has long been suspected to induce third-body PE wear resulting from particles delaminated into the joint space [3]. We report a higher midterm wear rate compared with other studies of Zr and CoCr with similar types of PE and head size (Table 1) and suggest the HA coating on the acetabular components could have influenced the PE wear. In support of this explanation, a recent study [20] with HA-coated implants showed 25% higher wear rates with Zr heads on UHMWPE (0.08 mm/year) compared with a similar study without HA-coated implants (0.06 mm/year) [23]. In the absence of HA particles, the PE wear rate in our patients might have been substantially lower in one, or both, groups. Thus, HA contamination could have overwhelmed an actual difference in PE wear rate of the groups. Another explanation for the high wear rates in our patients is the expected high-activity lifestyle of young patients [30]. Vigorous use of a THA may increase the risk of frictional heating and mechanical stress in the articulation [24] and lead to increased wear. For the Zr-on-PE bearing, this mechanism is well established as a partial tetragonal to monoclinic phase transformation resulting from in vivo physiologic mechanical and hydrothermal stresses [19, 21], which increase Zr surface roughening and grain pullout and provide the potential for accelerated PE wear. This theory explains why Zr-on-PE in our study and other studies [7, 17, 23] has a similar wear performance as CoCr-on-PE at midterm followup. Also, the continuous deterioration of Zr in vivo [21] explains the report of progressive wear with Zr-on-PE bearing couples from midterm to a minimum of

10 years' followup as described by Hernigou and Bahrami [17], and reduced survival of Zr-on-PE bearing couples (63%) at midterm (5.8 years') followup compared with an historical control group of identical implants with a 93% 9-year survival described by Allain et al. [1]. In comparison, we had no revisions at midterm.

Kim [20] reported the results of a prospective randomized study of 28-mm CoCr and Zr femoral heads on conventional PE. This is the only study to confirm a midterm wear analysis favoring Zr-on-PE (0.08 mm/year) versus CoCr-on-PE (0.17 mm/year) [20]. The method used to assess wear by Kim [20] was AutoCAD, whereas we used a validated software package (PolyWare) designed for measurements of head penetration of implants. Previous studies concerning Zr and CoCr have used numerous wear analysis techniques including a modified version of PolyWare [17], AutoCAD [22], Hip Analysis Suite [26], the manual technique of Livermore et al. [25], and roentgen stereophotogrammetric analysis [34]. Several factors may complicate direct comparison of wear results obtained by different wear analysis techniques, as each has specific limitations. These limitations have been described [16, 18, 34]. Wear estimates also may be dependent on numerous factors not attributed to the components or methods used to investigate similar topic studies, including the radiograph selected for baseline analysis (inclusion or exclusion of the creep period) [33], mobilization of the patient before the baseline radiograph, and possibly the number of radiographs analyzed.

Zr femoral heads were withdrawn from the commercial market in 2001 owing to incidents of head fracture after a change in the manufacturing procedure. We did not experience Zr head fractures at midterm followup, but reported cases of catastrophic results after revision of fractured ceramic heads [19, 27] encourage continued sharing of knowledge regarding Zr-on-PE bearing couples.

The published midterm wear results for Zr are contradictory, but our data do not suggest any advantage of Zr compared with CoCr heads. More evaluation of the long-term wear performance and potential side effects of Zr femoral heads is needed. The patients in this study will be followed continuously to identify possible differences in PE wear and complications at long-term followup.

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References

- Allain J, Le Mouel S, Goutallier D, Voisin MC. Poor eight-year survival of cemented zirconia-polyethylene total hip replacements. *J Bone Joint Surg Br.* 1999;81:835–842.
- Altman DG. *Practical Statistics for Medical Research.* 1995 ed. London, UK: Chapman & Hall; 2009.
- Bauer TW. Severe osteolysis after third-body wear due to hydroxyapatite particles from acetabular cup coating. *J Bone Joint Surg Br.* 1998;80:745.
- Bauer TW, Hirakawa K. Osteolysis: a generic problem. *Orthopedics.* 1995;18:791–794.
- Cales B. Zirconia as a sliding material: histologic, laboratory, and clinical data. *Clin Orthop Relat Res.* 2000;379:94–112.
- Clarke IC, Gustafson A. Clinical and hip simulator comparisons of ceramic-on-polyethylene and metal-on-polyethylene wear. *Clin Orthop Relat Res.* 2000;379:34–40.
- Cohn RM, Gonzalez Della Valle A, Peterson M, Cornell CN. Similar wear in total hip arthroplasties with metallic or zirconia femoral heads. *HSS J.* 2008;4:107–111.
- Collier MB, Kraay MJ, Rinnac CM, Goldberg VM. Evaluation of contemporary software methods used to quantify polyethylene wear after total hip arthroplasty. *J Bone Joint Surg Am.* 2003;85:2410–2418.
- Cooper RA, McAllister CM, Borden LS, Bauer TW. Polyethylene debris-induced osteolysis and loosening in uncemented total hip arthroplasty: a cause of late failure. *J Arthroplasty.* 1992;7:285–290.
- Cuckler JM, Bearcroft J, Asgian CM. Femoral head technologies to reduce polyethylene wear in total hip arthroplasty. *Clin Orthop Relat Res.* 1995;317:57–63.
- DeLee JG, Charnley J. Radiological demarcation of cemented sockets in total hip replacement. *Clin Orthop Relat Res.* 1976;121:20–32.
- Derbyshire B, Fisher J, Dowson D, Hardaker C, Brummitt K. Comparative study of the wear of UHMWPE with zirconia ceramic and stainless steel femoral heads in artificial hip joints. *Med Eng Phys.* 1994;16:229–236.
- Devane PA, Bourne RB, Rorabeck CH, Hardie RM, Horne JG. Measurement of polyethylene wear in metal-backed acetabular cups: I. Three-dimensional technique. *Clin Orthop Relat Res.* 1995;319:303–316.
- Devane PA, Bourne RB, Rorabeck CH, MacDonald S, Robinson EJ. Measurement of polyethylene wear in metal-backed acetabular cups: II. Clinical application. *Clin Orthop Relat Res.* 1995;319:317–326.
- Dowd JE, Sychterz CJ, Young AM, Engh CA. Characterization of long-term femoral-head-penetration rates: association with and prediction of osteolysis. *J Bone Joint Surg Am.* 2000;82:1102–1107.
- Ebramzadeh E, Sangiorgio SN, Lattuada F, Kang JS, Chiesa R, McKellop HA, Dorr LD. Accuracy of measurement of polyethylene wear with use of radiographs of total hip replacements. *J Bone Joint Surg Am.* 2003;85:2378–2384.
- Hernigou P, Bahrami T. Zirconia and alumina ceramics in comparison with stainless-steel heads: polyethylene wear after a minimum ten-year follow-up. *J Bone Joint Surg Br.* 2003;85:504–509.
- Hui AJ, McCalden RW, Martell JM, MacDonald SJ, Bourne RB, Rorabeck CH. Validation of two and three-dimensional radiographic techniques for measuring polyethylene wear after total hip arthroplasty. *J Bone Joint Surg Am.* 2003;85:505–511.
- Hummer CD 3rd, Rothman RH, Hozack WJ. Catastrophic failure of modular zirconia-ceramic femoral head components after total hip arthroplasty. *J Arthroplasty.* 1995;10:848–850.
- Kim YH. Comparison of polyethylene wear associated with cobalt-chromium and zirconia heads after total hip replacement: a prospective, randomized study. *J Bone Joint Surg Am.* 2005;87:1769–1776.
- Kim YH, Kim JS. Tribological and material analyses of retrieved alumina and zirconia ceramic heads correlated with polyethylene wear after total hip replacement. *J Bone Joint Surg Br.* 2008;90:731–737.

22. Kim YH, Kim JS, Cho SH. A comparison of polyethylene wear in hips with cobalt-chrome or zirconia heads: a prospective, randomised study. *J Bone Joint Surg Br.* 2001;83:742–750.
23. Kraay MJ, Thomas RD, Rimnac CM, Fitzgerald SJ, Goldberg VM. Zirconia versus Co-Cr femoral heads in total hip arthroplasty: early assessment of wear. *Clin Orthop Relat Res.* 2006;453:86–90.
24. Kumar P, Oka M, Ikeuchi K, Shimizu K, Yamamuro T, Okumura H, Kotoura Y. Low wear rate of UHMWPE against zirconia ceramic (Y-PSZ) in comparison to alumina ceramic and SUS 316L alloy. *J Biomed Mater Res.* 1991;25:813–828.
25. Livermore J, Ilstrup D, Morrey B. Effect of femoral head size on wear of the polyethylene acetabular component. *J Bone Joint Surg Am.* 1990;72:518–528.
26. Martell JM, Berdia S. Determination of polyethylene wear in total hip replacements with use of digital radiographs. *J Bone Joint Surg Am.* 1997;79:1635–1641.
27. Oldenburg M, Wegner R, Baur X. Severe cobalt intoxication due to prosthesis wear in repeated total hip arthroplasty. *J Arthroplasty.* 2008 Oct 1. [Epub ahead of print].
28. Piconi C, Maccauro G, Angeloni M, Rossi B, Learmonth ID. Zirconia heads in perspective: a survey of zirconia outcomes in total hip replacement. *Hip Int.* 2007;17:119–130.
29. Saikko V. Wear of polyethylene acetabular cups against zirconia femoral heads studied with a hip-joint simulator. *Wear.* 1994; 176:207–212.
30. Schmalzried TP, Huk OL. Patient factors and wear in total hip arthroplasty. *Clin Orthop Relat Res.* 2004;418:94–97.
31. Schmalzried TP, Jasty M, Harris WH. Periprosthetic bone loss in total hip arthroplasty: polyethylene wear debris and the concept of the effective joint space. *J Bone Joint Surg Am.* 1992;74:849–863.
32. Schmalzried TP, Shepherd EF, Dorey FJ, Jackson WO, dela Rosa M, Fa'vae F, McKellop HA, McClung CD, Martell J, Moreland JR, Amstutz HC. The John Charnley Award. Wear is a function of use, not time. *Clin Orthop Relat Res.* 2000;381: 36–46.
33. Sychterz CJ, Engh CA Jr, Yang A, Engh CA. Analysis of temporal wear patterns of porous-coated acetabular components: distinguishing between true wear and so-called bedding-in. *J Bone Joint Surg Am.* 1999;81:821–830.
34. von Schewelov T, Sanzen L, Borlin N, Markusson P, Onsten I. Accuracy of radiographic and radiostereometric wear measurement of different hip prostheses: an experimental study. *Acta Orthop Scand.* 2004;75:691–700.
35. von Schewelov T, Sanzen L, Onsten I, Carlsson A, Besjakov J. Total hip replacement with a zirconium oxide ceramic femoral head: a randomised roentgen stereophotogrammetric study. *J Bone Joint Surg Br.* 2005;87:1631–1635.
36. Wan Z, Dorr LD. Natural history of femoral focal osteolysis with proximal ingrowth smooth stem implant. *J Arthroplasty* 1996; 11:718–725.