Inferior Survival of Hydroxyapatite versus Titanium-coated Cups at 15 Years

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Abstract Hydroxyapatite (HA) particles have long been suspected to disintegrate from implant surfaces, become entrapped in joint spaces of orthopaedic bearing couples, and start a cascade leading to progressive polyethylene (PE) wear, increased osteolysis, and aseptic loosening. We compared cup revision at 15 years' followup in a randomized group of patients with 26 cementless THA components with titanium (Ti) versus first-generation HA coating. We also assessed radiographic PE wear and osteolysis to the 12-year followup or end point revision at a minimum of 5 years (mean, 10.9 years; range, 5–12.6 years). Two Ti-coated cups (17%) and eight HA-coated cups (57%) were revised at 15 years' followup. Femoral head penetration rate was 0.46 mm/year (standard deviation, 0.26) with the HA-coated cups ($n = 12$) and 0.38 mm/year (standard deviation, 0.14) with the Ti-coated cups ($n = 10$); we observed a wide variance of linear wear with the HA-coated cups. We also observed a positive association between high wear rate and revision, and between a high volume of osteolysis and revision. Our findings suggest inferior survival of medium-thickness spray-dried HA-coated cups with individual cases of excessive PE wear and premature cup failure. These

findings apply to first-generation modular cups and may not apply to other cup designs and new HA-coating technologies.

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

Introduction

Wear of the PE component is widely regarded as the primary factor limiting longevity of THA [16]. If the origins of premature or accelerated wear can be identified, then it may be possible to alter or improve the design and enhance performance and survival of THAs [27]. HA coatings reportedly provide bony ingrowth and improved initial implant stability [41, 44]. Rahbek et al. suggested enhanced fixation and reduction in radiolucencies are related to a superior sealing effect of the HA coating reducing wear particle migration into the bone-implant interface [37, 38]. The sealing effect of HA coating is believed to reduce macrophage-induced osteolysis and prolong the lifespan of uncemented implants [14, 38, 41].

Reliable clinical fixation, osseointegration, and longer-term revision rates less than 1% for HA-coated femoral components have been reported [12, 13, 30, 36, 39, 47]. Two studies of HA-coated versus nonHA-coated acetabular components showed equal or improved fixation and reduced periprosthetic radiolucencies [14, 41], but reports of PE wear rates reveal values higher than expected (range, 0.15–0.32 mm/year) with HA-coated cups and medium-term revision rates between 13% and 40% [7, 13, 21, 29, 40]. In some situations, such as those in which the HA coating was applied directly to a smooth implant surface and subsequently flaked off, high rates of early failure

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Each author certifies that his or her 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 for participation in the study was obtained. This study was performed at Aarhus University Hospital.

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might be readily explained [13, 29]. The major overall concern is disintegration of the HA coating in vivo, resulting in loss of fixation, formation of particulate HA debris, and abrasive third-body wear between the articulating surfaces of the prosthetic components [3, 48]. Supporting this concern, HA particles have been detected on the PE surface of retrieved components [4, 9], and loose HA particles may increase production of excessive PE particles, leading to increased PE wear and liner revision, premature periprosthetic osteolysis, and aseptic implant loosening [4, 33]. In general, release of HA particles from the implant surface could generate a clinical problem with few, if any, early warning signs [6, 33].

We therefore asked (1) whether there was a difference in cup survival rates with or without HA coating, and whether any difference in survival rates was associated with (2) the amount and rate of wear and (3) the amount of osteolysis.

Materials and Methods

In 1991 and 1992, we prospectively enrolled 27 patients (28 hips) scheduled for primary THA and randomly allocated them to receive either a Ti- ($n = 13$) or an HA-coated ($n = 15$) implant for a femoral stem migration study [47]; one patient had bilateral surgery with one Ti hip and one HA hip. A followup of those patients is reported here. The study was approved by the local ethical committee and informed consent was obtained from all participants. We included patients with osteoarthritis of the hip and age older than 18 years and younger than 67 years, and excluded patients with congenital hip disorders, osteoporosis (ie, those under medical treatment), metabolic bone disorders, rheumatoid arthritis, malignant disease, and femoral neck fractures. All patients meeting the inclusion and exclusion criteria were offered participation in the migration study until allocation of 28 hips was reached. No patient offered enrollment refused to participate. All components (femoral stems and acetabular cups) were similar except for the coating (which for a given patient was the same for the stem and the cup). One group had implants with porous Ti coating with HA and the other group had implants with a similar porous Ti coating without HA. A sample size calculation based on an expected clinically relevant difference of 40% in revision between the groups suggested 12 patients per group with a power of 49 ($\alpha = 0.05$). The difference in proportion was based on the existing literature of similar hemispheric cups with longer-term followup [26, 29]. Distributions of gender, age, weight, cup size, liner thickness, average followup, and hip side were similar between the patient groups (Table 1). The patients were randomized on the day of surgery. Three patients from the original group of 27

Table 1. Patient demographics (mean, range)

Input variables	HA group	Ti group
Age (years)	57 (49–63)	59 (50–66)
Cup (mm)	54 (46–70)	52 (48–62)
Liner (mm)	4.8 (3.4–11.5)	4.0 (3.4–6.5)
Weight (kg)	73.3 (54–96)	70.3 (51–98)
Male/female	7/7	3/8
Right/left	8/4	5/5
Radiographic followup (years)	10.6 (5.0–12.6)	11.6 (5.6–12.5)

HA = hydroxyapatite; Ti = titanium; PE = polyethylene.

Fig. 1 The diagram shows the patients available for evaluation of revision, PE wear, and osteolysis in the two groups; the numbers and reasons for drop outs; and the time and reasons for cup revision (HA = Hydroxyapatite; Ti = Titanium; A = Aseptic loosening; O = Osteolysis; T = Trauma).

patients (28 hips) were lost in each group (Fig. 1). One patient who entered the study with bilateral surgery (one Ti hip and one HA hip), died 1 year after surgery of causes unrelated to the THA. According to patient records, neither of the patient's THAs was revised and the patient was excluded from analysis in this study (survival, wear, osteolysis). Twenty-six patients remained for determination of survival based on revision at 15 years. Radiographs of 22 of the 26 patients were available to measure linear wear (accessible postoperative and followup radiographs), and 25 patients had radiographs (last followup) available to

Fig. 2 A Universal® acetabular metal shell with plasma porous spray coating and Hexloc® locking mechanism for the PE liner are shown. (Photograph courtesy of and reprinted with permission of Biomet Denmark ApS, Horsens, Denmark.)

quantify osteolysis (Fig. 1). The minimum duration of radiographic followup was 5 years (mean, 10.9 years; range, 5.0–12.6 years) for the HA group and 5.6 years (mean, 11.1 years; range, 5.6–12.5 years) for the Ti group. The patients who did not have revision surgery or were deceased at 12 years' followup did have a standard radiographic followup. We assessed the rate of revision THAs among the 26 patients (26 hips) in the groups by reading through patient records where a description of the revision surgery was noted. The information for all 26 patients was crosschecked with 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. The patients' information in the registry was the same as in our records.

One surgeon (CB) performed all operations by the posterolateral surgical approach. The cups were fixed with two to three titanium screws. The femoral component was a solid Ti6Al4V alloy core Universal® Bi-Metric® design (Biomet Inc, Warsaw, IN) with a collarless straight stem and a circumferential Ti plasma spray porous coating to the proximal quarter. The acetabular metal shell was a hemispheric Ti plasma spray porous Universal® design (Biomet Inc) with a rim flair, holes for optional bone screw supplemental fixation, and a Hexloc® locking mechanism (Biomet Inc) for the liner (Fig. 2). The femoral heads (Biomet Inc) were 28-mm chrome-cobalt alloy. The liner was 10° face GUR 415 bar extruded ultrahigh molecular weight PE (UHMWPE) in all cases. A postextrusion thermal cycle (annealing), known to slightly increase crystallinity, density, and rigidity, was conducted before machining to maintain the PE bar in stable shape. To reduce oxidation, the PE was packaged in an inert argon environment. The overall mechanical properties for this PE reportedly are superior (Table 2) to the recommended standard of the American Society of Testing and Materials [2]. We used six different PE thicknesses (range, 3.39–11.46 mm). The Ti-coated components had a pore size of

Table 2. Properties of UHMWPE*

PE properties	ASTM standard	Biomet GUR 415 extruded bar
Molecular weight	3 million	3–5 million
Ultimate tensile strength	4000 psi	4949 psi
Tensile yield	2800 psi	3600 psi
Izod impact	20 ft-lb	No break
Elongation to failure	200%	500%

* Information provided by the manufacturer; ASTM = American Society of Testing and Materials; UHMWPE = ultrahigh molecular weight polyethylene.

300 µm. The HA-coated components had a similar Ti porous coating with an additional 50- to 75-µm layer of spray-dried synthetic HA deposited by plasma spraying. The crystallinity was 90%. The surface roughness (Ra) was 41 µm for the HA components and 47 µm for the Ti components [47].

We collected all available hard-copy postoperative anteroposterior (AP) radiographs and latest followup radiographs. Intermediate followup radiographs at 3 months, 6 months, 1 year, and 5 years also were available for 22 patients with adequate followup. The postoperative (baseline) radiographs were obtained after partial weight-bearing and mobilization within a few days after surgery. Five to six AP radiographs were available for all patients. The radiographs were digitized with a high-resolution optical scanner (Mustek® P3600 A3 pro, Mustek Systems, Inc, Irvine, CA) to 100% scale and 300 dpi. Cross-table lateral radiographs also were available, but we chose not to include them for analysis owing to their lesser quality. Femoral head penetration was measured with a computer-assisted method (PolyWare™ Digital Version 5.10; Draftware Developers, Inc, Vevay, IN) [20] on AP radiographs of the hip. This shadow-casting method [15] uses a digital edge detection algorithm to fit circles to the peripheries of the femoral head and acetabular cup. Based on some

assumptions this computer-assisted technology applies over the radiograph a three-dimensional solid model of the acetabular component and femoral head based on back-projection of the radiographs [19]. Linear wear was measured in the plane of the AP radiograph by the software with an accuracy of approximately 0.15 mm [19].

The quality of the digitized AP radiographs generally was good and we rarely manually overruled the automatic circle fitting. PE wear analysis was performed retrospectively in intervals among the six followups by one observer (CS), who was blinded to the groups. Precision of wear measurement analysis (intraobserver error) with the computer-assisted method was evaluated for the one observer (CS) by double analysis 1 month apart for 11 patients who had 12 years of followup. The mean absolute difference with the first and second analyses was 0.08 mm (standard deviation [SD], 0.28 mm).

Radiographic assessment of osteolysis was performed blinded by an experienced orthopaedic consultant (KS) with a subspecialty in hip arthroplasty. Twenty-five end-point radiographs were available for evaluation of osteolysis. Osteolytic zones were marked by the surgeon in India ink directly on the radiograph (Fig. 3). The radiographs then were digitized again and osteolysis quantified by a function in the computer-assisted method (PolyWareTM) developed by Devane et al. [20]. The osteolytic areas traced on the AP radiograph were automatically scaled for the known size of the femoral head and converted to a volumetric measurement (cubic millimeters). The software (PolyWareTM) used the assumption that the lesion was the same size on the AP and the cross-table lateral radiographs. Precision of quantitative osteolysis with the computer-assisted method also was evaluated for one observer (LLA) by double analysis 1 month apart for 25 patients. The mean absolute difference with the first and second analyses was 44.8 mm³ (SD, 62.89 mm³).

We compared survival rates of the cups by a log-rank test at 15 years' followup. According to a Shapiro-Wilk test [1], head penetration and wear rates were normally distributed when converted to log scale. Similarities or differences in variances of the log scale wear data for the two groups were tested by an F test. The log mean values of the two groups were compared by a two-sample t test with unequal variances (head penetration) and a two-sample t test with equal variance (wear rates). Head penetration (mm) of the longest followup per patient (minimum 5 years, maximum 12.6 years) and head penetration rates (mm/year) are presented on a normal scale for interpretational reasons. Mean osteolysis between the groups was compared by Mann-Whitney U-test. The associations between wear rate and revision and between osteolysis and revision also were assessed by a Mann-Whitney U-test. The Intercooled Stata[®] 9.0 (StataCorp

Fig. 3 A 12-year followup AP radiograph shows a large osteolytic lesion in the acetabulum marked in India ink. PE wear is evident because the femoral head is decentralized. Clinically, the patient had pain and discomfort. Revision surgery revealed a loose cup, a large osteolytic lesion behind the acetabular component, and metallosis of the tissue. The femoral stem is marked with tantalum beads for radiostereometric analysis.

LP, College Station, TX) package was used for statistical computations.

Results

At last followup, more ($p = 0.045$) HA cups had been revised than Ti cups: eight of 14 HA cups (57%) and two of 12 Ti cups (17%) (Fig. 4). At revision surgery, aseptic loosening, massive acetabular osteolysis, and metallosis were clinically evident for all revised cups, except for one Ti cup that was revised after the patient experienced a traumatic fall at 5.6 years. All of the cups (Ti and HA) revised within the 12-year followup had wear rates greater than 0.4 mm/year or osteolysis greater than 25,000 mm³ (Fig. 5).

The head penetration rate for the HA group at a mean of 10.6 years (0.46 mm/year; SD, 0.26; range, 0.16–0.90 mm/year) was similar to ($p = 0.33$) that of the Ti group (0.38 mm/year; SD, 0.14; range, 0.20–0.72 mm/year) at a

Fig. 4 A Kaplan-Meier survival graph shows poor survival ($p = 0.045$) of the HA-coated cup ($n = 14$) compared with the Ti-coated cup ($n = 12$).

Fig. 5 The graph shows an association between revised cups (solid symbols) and a wear rate greater than 0.4 mm/year (dotted horizontal line) or osteolysis greater than 25,000 mm³ (dotted vertical line). The one Ti cup (open triangle) with a wear rate greater than 0.4 mm/year and no revision belonged to a patient who died at 5.7 years' followup of causes unrelated to THA.

mean of 11.1 years. Mean head penetration in the HA group at a mean of 10.6 years (4.8 mm; SD, 2.6; range, 1.97–10.56 mm) also was similar to ($p = 0.25$) that of the Ti group (3.8 mm; SD, 0.9; range, 2.51–5.36 mm) at a mean of 11.1 years. Wear of the PE continued in both study groups throughout the followup (Fig. 6). During the first 6 months, the PE wear was quite large in both groups, illustrating a combination of wear and bedding-in. After 1 year, linear head penetration continued in both study groups but at a less steep curve. Reflected by variance, the distribution of wear was wider ($p = 0.017$) in the HA group (SD, 2.6; range, 1.97–10.56 mm) than in the Ti group (SD, 0.9; range, 2.51–5.36 mm). This indicates the HA coating affected femoral head penetration with some of the investigated components because some patients in the

Fig. 6 The graph shows a mean linear PE wear throughout the 12-year followup period in the HA and Ti groups. The steep wear curve during the first year of followup is a combination of wear and creep.

group had large head penetration with subsequent component failure and revision whereas other patients had low head penetration and normal component longevity. We observed a greater ($p = 0.0001$) wear rate in patients who had revision surgery than in patients who did not have revision surgery.

We observed a higher ($p = 0.003$) volume of osteolysis in patients who had revision surgery. Osteolytic lesions (Fig. 3) were visible on the plain radiographs in all 25 patients at the latest available followup. The mean measure of osteolysis was 9320 mm³ (SD, 8838; range, 178–29,028 mm³) in the HA group and 7531 mm³ (SD, 10,915; range, 1091–34,698 mm³) in the Ti group ($p = 0.30$).

Discussion

The osteoconductive properties of HA-coated titanium implants are well documented [46]. However, theories of coating degradation resulting in particulate HA-induced third-body wear [5, 8, 33] have long been discussed. This study was initiated to evaluate the potential disadvantages of HA-coated implants for THA including (1) survival, (2) increased wear, and (3) increased osteolysis.

Limitations of the study include the small number of patients in this randomized patient group, which originally was powered for radiostereometric migration analysis of the femoral stems [47], and seemingly the small sample size likely explains the lack of statistical significance with comparison of wear and osteolysis (ie, a Type 2 error). Although the groups were randomized, there were an equal number of each gender in the HA group, but more females than males in the Ti group, and this potentially could have contributed to a higher wear rate in the HA group.

Hard-copy radiographs of four patients (two with Ti cups, two with HA cups) were lost which could introduce some selection bias. We compared the mean wear of the two groups from the postoperative baseline until the last radiograph available (revision, death, or the 12-year followup) at a minimum of 5 years. It would be desirable to compare all patients at the same and longest followup time; however, excluding revisions from a wear analysis potentially removes the worst cases of wear and thus we chose to include all available patients to the last available radiograph. The level of activity was not controlled for and this could have influenced wear. The computerized methods for plain radiographs are not as accurate as retrieval analysis or radiostereometric analysis and limitations have been described [23]. However, the method used in this study was validated for clinical evaluation of longer-term followups and series of high wear [27]. We only used AP images, as the cross-table lateral radiographs were of varying projection and quality, and thus we consciously restricted wear analysis to two-dimensional results. Two-dimensional and three-dimensional measurements of femoral head penetration in the PE liner correlate well, and for most patients (95%) PE wear can be estimated from AP radiographs alone [50].

We report high 15-year cup revision rates of 57% and 17% for HA- and Ti-coated cups, respectively (Fig. 4). A recent study from the Finnish Arthroplasty Registry suggests the most common reason for revision of the Universal[®] cup (combined data for the Ti- and HA-coated cups) is wear leading to liner exchange, with a 13-year revision rate of 26% [24]. Other studies of the same

acetabular component reveal revision rates between 13% and 26% at means of 7 and 10 years followup [28, 32]. Numerous authors have described a larger main group of well-performing cups with a smaller group of cup failures attributable to osteolysis, wear, aseptic loosening, and PE fracture (Table 3). Apparently, there is no clear association between worn failing implants and the clinical performance [29, 33], and thus expansile (cystic) osteolysis and loosening may progress without warning signs [5, 33, 42].

The higher variation of femoral head penetration in the HA group as opposed to the Ti group (SD 0.26 mm/year and 0.14 mm/year, respectively) supports the concerns expressed in other studies with individual cases of high PE wear with HA-coated cups leading to implant failure [7, 8, 11, 21, 29, 42]. The cases of high PE wear in our study could be related to HA particles separating from the coating leading to increased backside wear and articulate wear on the PE, a mechanism described by Bauer, Morscher et al., and Rokkum et al. [4, 33, 43]. Disintegration of the HA coating is influenced by numerous factors, including the purity of HA, manufacturing, crystallinity, porosity, method of coating, the thickness of the HA coating, the surface on which HA is deposited (smooth or rough), the adhesive strength of HA to the substrate [33], and the speed of resorption [8, 35, 45]. Calcium phosphate coatings have been applied plasma-sprayed with different quality and coating thicknesses ranging from 300 μ m [33, 43], over 150 μ m [42], to 40 μ m [41]. Thinner plasma-sprayed HA coatings (50 μ m) have been recommended, as they give a stronger fixation and reduce the risk of HA fracture [44]. Today plasma-sprayed HA deposition has been replaced by

Table 3. Studies of uncemented HA coated hemispherical acetabular components

Study	Cup implant	Number (hips)	Mean age (years)	Revisions	Reason for failure	Wear	Mean followup (years)
Blacha [7]	ABG I	65	44	23%	W, O, AsL	–	6
Canales et al. [11]	ABG I	107	58	–	O	0.17 mm/year	10
Chang et al. [13]	Omnifit	82	54	14.3%	AsL	–	7
Delank et al. [18]	ABG I	193	–	13.9%	W, O	0.23 mm/year	5
Duffy et al. [21]	ABG I	97	49	24%	W, O	0.32 mm/year	5.75
Eskelinen et al. [24]	Universal Cup*	858	< 55	26%	W	–	13
Gallo et al. [25]	ABG I	137	46	37.2%	O, AsL	0.29 mm/year R	12
Isaac et al. [28]	Universal Cup	49	57	13%	PF, W	–	7.6
Kim et al. [29]	Omnifit	70	49	39.5% (8 years)	O	0.15 mm/year	7
Meijerink et al. [32]	Universal Cup	19	31	26%	AsL	–	10.4
Ohnsorge et al. [34]	ABG I	135	55	28%	W	–	8.5
Rohrl et al. [41]	Reflection	22	56	0%	–	0.2 mm/year	5
Rokkum et al. [42]	“Smooth” Cup	94	56	22.5%	W, O	0.39 mm/year R	6.7
Current study	Universal Cup	14	58	57% (15 years)	AsL, O	0.46 mm/year	11

* HA and Ti coating combined, HA = hydroxyapatite, Ti = titanium, O = osteolysis, AsL = aseptic loosening, PF = polyethylene fracture, W = polyethylene wear, R = retrieved cups only.

much thinner (approximately 5 µm) and electrochemically deposited HA coatings that ensure even distribution and quick resorption [17], but medium- and long-term results are yet to be seen.

The femoral head penetration rates of the Ti and HA groups are high compared with other studies (Table 3) reporting wear of intermediate or long-term followup. The majority of time-dependent deformation (creep or bedding-in) occurs within the first postoperative year [26, 49]. We chose to include the first year because wear along with creep does occur in this period, and possibly the amount and speed of creep are different with different PEs and sterilization methods. Another explanation for the high wear we see is the inferior quality of the UHMWPE liner in combination with a poor PE locking mechanism (Hexloc®, Biomet Inc) [10]. Also, the screw hole-designed acetabular cups introduce an exit for PE wear debris directly to the bone and an entrance for HA particles to accelerate back-side wear [21] that cannot be distinguished from articulate wear [31].

An osteolysis threshold of a PE wear rate of 0.1 mm/year has been described [22], and numerous reports of wear with HA-coated cups (Table 3) have much higher annual wear rates. We found a femoral head penetration rate greater than 0.4 mm/year was associated with cup failure and revision. PE particles liberated in the wear process induce a biologic reaction, resulting in osteolysis [16]. Massive osteolysis leads to loosening and we saw a tendency for cups with osteolysis greater than 25,000 mm³ to become loose and necessitate revision (Fig. 5).

A midterm RSA study reported similar fixation of a press-fit hemispherical porous-coated titanium alloy cup with and without HA-coating [41], but studies reporting wear, osteolysis, and revision reveal a high failure rate with various HA-coated cups (Table 3). For some cups, there is a plausible explanation of failure, eg, in cases of HA coating applied to smooth surfaces [13, 29, 42], very thick coatings [33, 42], the presence of screw holes [7, 25], a poor locking mechanism [32], and conventional PE. However, for other HA-coated cup designs, the reasons for the wear rate, osteolysis, and revision are not entirely transparent [7, 21, 25, 34] and raise concern regarding continued use of HA coating for acetabular cups. Generalizability of our results based on discontinued components is unclear. We therefore suggest further investigations to clarify the performance (survival, wear, osteolysis) of newer HA coating technologies, such as thinner HA coatings and electrochemical HA coatings, cross-linked PEs, and newer implant designs. We advise close followup of patients with HA-coated cups similar to those used in our study.

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References

- Altman DG. *Practical Statistics for Medical Research*. 1995 ed. London, UK: Chapman & Hall; 2009.
- ASTM. Standard specification for ultra-high molecular-weight polyethylene powder and fabricated form for surgical implants. ASTM Standard F648. West Conshohocken, PA: American Society for Testing and Materials; 1984.
- Bauer TW. Hydroxyapatite: coating controversies. *Orthopedics*. 1995;18:885–888.
- 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, Taylor SK, Jiang M, Medendorp SV. An indirect comparison of third-body wear in retrieved hydroxyapatite-coated, porous, and cemented femoral components. *Clin Orthop Relat Res*. 1994;298:11–18.
- Benko TZ, Santiago-Martin A, Ruddlesdin C, Selzer G. Aseptic loosening of 2 rim-fix, hydroxyapatite-coated acetabular cups. *J Arthroplasty*. 2002;17:519–523.
- Blacha J. High osteolysis and revision rate with the hydroxyapatite-coated ABG hip prostheses: 65 hips in 56 young patients followed for 5–9 years. *Acta Orthop Scand*. 2004;75:276–282.
- Bloebaum RD, Beeks D, Dorr LD, Savory CG, DuPont JA, Hofmann AA. Complications with hydroxyapatite particulate separation in total hip arthroplasty. *Clin Orthop Relat Res*. 1994;298:19–26.
- Bloebaum RD, Zou L, Bachus KN, Shea KG, Hofmann AA, Dunn HK. Analysis of particles in acetabular components from patients with osteolysis. *Clin Orthop Relat Res*. 1997;338:109–118.
- Boby JD, Tanzer M, Krygier JJ, Dujovne AR, Brooks CE. Concerns with modularity in total hip arthroplasty. *Clin Orthop Relat Res*. 1994;298:27–36.
- Canales CV, Panisello Sebastia JJ, Herrera RA, Peguero BA, Martinez MA, Herrero BL, Garcia-Dihinx L. Ten-year follow-up of an anatomical hydroxyapatite-coated total hip prosthesis. *Int Orthop*. 2006;30:84–90.
- Chambers B, St Clair SF, Froimson MI. Hydroxyapatite-coated tapered cementless femoral components in total hip arthroplasty. *J Arthroplasty*. 2007;22:71–74.
- Chang JK, Chen CH, Huang KY, Wang GJ. Eight-year results of hydroxyapatite-coated hip arthroplasty. *J Arthroplasty*. 2006;21:541–546.
- Coathup MJ, Blackburn J, Goodship AE, Cunningham JL, Smith T, Blunn GW. Role of hydroxyapatite coating in resisting wear particle migration and osteolysis around acetabular components. *Biomaterials*. 2005;26:4161–4169.
- 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.
- Daugaard H, Elmengaard B, Bechtold JE, Soballe K. Bone growth enhancement in vivo on press-fit titanium alloy implants with acid etched microtexture. *J Biomed Mater Res A*. 2008;87:434–440.

18. Delank KS, Drees P, Menzel N, Hansen T, Duschner H, Eckardt A. Increased polyethylene wear after cementless ABG I total hip arthroplasty. *Arch Orthop Trauma Surg*. 2006;126:509–516.
19. 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.
20. 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.
21. Duffy P, Sher JL, Partington PF. Premature wear and osteolysis in an HA-coated, uncemented total hip arthroplasty. *J Bone Joint Surg Br*. 2004;86:34–38.
22. Dumbleton JH, Manley MT. Comment on: J Arthroplasty. 2003;18:506–510. “The lysis threshold”: an erroneous and perhaps misleading concept? By Harris WH. *J Arthroplasty*. 2003;18:537–538.
23. 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.
24. Eskelinen A, Remes V, Helenius I, Pulkkinen P, Nevalainen J, Paavolainen P. Uncemented total hip arthroplasty for primary osteoarthritis in young patients: a mid-to long-term follow-up study from the Finnish Arthroplasty Register. *Acta Orthop*. 2006;77:57–70.
25. Gallo J, Langova K, Havranek V, Cechova I. Poor survival of ABG I hip prosthesis in younger patients. *Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub*. 2008;152:163–168.
26. Hopper RH Jr, Young AM, Engh CA Jr, McAuley JP. Assessing the pattern of femoral head penetration after total hip arthroplasty. *J Arthroplasty*. 2004;19:22–29.
27. 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.
28. Isaac DL, Forder J, Skyrme AD, James SE. The Biomet Bi-Metric total hip arthroplasty and universal acetabular cup: high polyethylene failure rate in the medium term. *J Arthroplasty*. 2007;22:697–700.
29. Kim SY, Kim DH, Kim YG, Oh CW, Ihn JC. Early failure of hemispheric hydroxyapatite-coated acetabular cups. *Clin Orthop Relat Res*. 2006;446:233–238.
30. Lee JM, Lee CW. Comparison of hydroxyapatite-coated and non-hydroxyapatite-coated noncemented total hip arthroplasty in same patients. *J Arthroplasty*. 2007;22:1019–1023.
31. Lieberman JR, Kay RM, Hamlet WP, Park SH, Kabo JM. Wear of the polyethylene liner-metallic shell interface in modular acetabular components: an in vitro analysis. *J Arthroplasty*. 1996;11:602–608.
32. Meijerink HJ, Gardeniers JW, Buma P, Lemmens JA, Schreurs BW. Hydroxyapatite does not improve the outcome of a bipolar hemiarthroplasty. *Clin Orthop Relat Res*. 2004;421:143–150.
33. Morscher EW, Hefti A, Aebi U. Severe osteolysis after third-body wear due to hydroxyapatite particles from acetabular cup coating. *J Bone Joint Surg Br*. 1998;80:267–272.
34. Ohnsorge JA, Davis J, Maus U, Saklak M, Weisskopf M, Wirtz DC. Early polyethylene wear and excessive acetabular granuloma in an uncemented HA-coated total hip arthroplasty: midterm results of a prospective study. *HSS J*. 2006;2:114–120.
35. Overgaard S, Soballe K. Polyethylene wear, osteolysis and acetabular loosening with an HA-coated hip prosthesis. *J Bone Joint Surg Br*. 2000;82:305–306.
36. Paulsen A, Pedersen AB, Johnsen SP, Riis A, Lucht U, Overgaard S. Effect of hydroxyapatite coating on risk of revision after primary total hip arthroplasty in younger patients: findings from the Danish Hip Arthroplasty Registry. *Acta Orthop*. 2007;78:622–628.
37. Rahbek O, Overgaard S, Jensen TB, Bendix K, Soballe K. Sealing effect of hydroxyapatite coating: a 12-month study in canines. *Acta Orthop Scand*. 2000;71:563–573.
38. Rahbek O, Overgaard S, Lind M, Bendix K, Bunger C, Soballe K. Sealing effect of hydroxyapatite coating on peri-implant migration of particles: an experimental study in dogs. *J Bone Joint Surg Br*. 2001;83:441–447.
39. Reikeras O, Gunderson RB. Excellent results of HA coating on a grit-blasted stem: 245 patients followed for 8–12 years. *Acta Orthop Scand*. 2003;74:140–145.
40. Reikeras O, Gunderson RB. Long-term results of HA coated threaded versus HA coated hemispheric press fit cups: 287 hips followed for 11 to 16 years. *Arch Orthop Trauma Surg*. 2006;126:503–508.
41. Rohrl SM, Nivbrant B, Strom H, Nilsson KG. Effect of augmented cup fixation on stability, wear, and osteolysis: a 5-year follow-up of total hip arthroplasty with RSA. *J Arthroplasty*. 2004;19:962–971.
42. Rokkum M, Brandt M, Bye K, Hetland KR, Waage S, Reigstad A. Polyethylene wear, osteolysis and acetabular loosening with an HA-coated hip prosthesis: a follow-up of 94 consecutive arthroplasties. *J Bone Joint Surg Br*. 1999;81:582–589.
43. Rokkum M, Reigstad A, Johansson CB. HA particles can be released from well-fixed HA-coated stems: histopathology of biopsies from 20 hips 2–8 years after implantation. *Acta Orthop Scand*. 2002;73:298–306.
44. Soballe K. Hydroxyapatite ceramic coating for bone implant fixation: mechanical and histological studies in dogs. *Acta Orthop Scand Suppl*. 1993;255:1–58.
45. Soballe K, Overgaard S. The current status of hydroxyapatite coating of prostheses. *J Bone Joint Surg Br*. 1996;78:689–691.
46. Soballe K, Overgaard S, Hansen ES, Brokstedt-Rasmussen H, Lind M, Bunger C. A review of ceramic coatings for implant fixation. *J Long Term Eff Med Implants*. 1999;9:131–151.
47. Soballe K, Toksvig-Larsen S, Gelinek J, Fruensgaard S, Hansen ES, Ryd L, Lucht U, Bunger C. Migration of hydroxyapatite coated femoral prostheses: a Roentgen Stereophotogrammetric study. *J Bone Joint Surg Br*. 1993;75:681–687.
48. Sun L, Berndt CC, Khor KA, Cheang HN, Gross KA. Surface characteristics and dissolution behavior of plasma-sprayed hydroxyapatite coating. *J Biomed Mater Res*. 2002;62:228–236.
49. 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.
50. Sychterz CJ, Yang AM, McAuley JP, Engh CA. Two-dimensional versus three-dimensional radiographic measurements of polyethylene wear. *Clin Orthop Relat Res*. 1999;365:117–123.