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Influence of polyethylene and femoral head surface quality on wear: A retrieval study

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Abstract Thirty-two polyethylene sockets and 22 femoral heads were retrieved because of aseptic loosening more than 9 years after total hip arthroplasty. The volumetric wear rates of the retrieved polyethylene sockets were significantly greater in those coupled with an alumina head ($P<0.05$). The retrieved alumina heads showed significantly better surface roughness and roundness than heads of Co-Cr and of stainless steel ($P<0.05$). However, no significant difference was found in polyethylene quality demonstrated as fusion defects among the three different groups. The present study suggests that maintaining better surface roughness and roundness of the femoral heads does not always result in an in vivo reduction of polyethylene wear.

Résumé Nous avons évalué 32 cupules acetabulaires en polyéthylène et 22 têtes fémorales retirées à cause d'un descellement aseptique plus de 9 ans après une arthroplastie totale de la hanche. Les taux d'usure volumétriques des cupules en polyéthylène étaient notablement plus élevés dans les couples avec une tête en alumine ($P<0.05$). Les têtes en alumine montraient une rugosité et une sphéricité notablement meilleure que les têtes métalliques en Co-Cr ou en acier inoxydable. Cependant, aucune différence importante ne fut trouvée dans la qualité du polyéthylène pouvant démontrer des défauts de fusion parmi les trois groupes. L'étude présente suggère que le maintien d'une meilleure rugosité et sphéricité de la surface des têtes fémorales ne provoque pas toujours une diminution de l'usure du polyéthylène in vivo.

Introduction

Reduction of polyethylene wear and elimination of wear-induced osteolysis are essential to improve the longevity of total hip arthroplasty. Cross-linked polyethylene and ceramic heads are currently used for polyethylene wear reduction [17, 38, 39]. These materials have been applied to total hip arthroplasty based on the encouraging results of a number of wear simulator tests [6, 22, 23, 26, 27, 38]. However, wear simulator tests do not always accurately reflect in vivo wear [4, 20, 29, 36], so clinical applications of new materials based on simulator tests have sometimes been misleading [21]. Components retrieved after a long period in situ should be analyzed to determine the mechanism of polyethylene wear in vivo.

In the present study, three types of polyethylene sockets and femoral heads retrieved more than 9 years after total hip arthroplasty were evaluated to determine the influence of polyethylene and femoral head surface quality on wear.

Materials and methods

Thirty-two all-polyethylene acetabular components and 22 femoral heads were evaluated in this study. They had all been retrieved during revision surgery more than 9 years after implantation and included three types of components: Bioceram (Kyocera Corporation, Kyoto, Japan), Müller and Charnley components. All components had been fixed with cement and were revised because of aseptic loosening (Table 1). As seen from Table 2 there were no statistically significant differences between the three groups of patients.

The Bioceram component had a 28 mm diameter polycrystalline alumina head (AY-7, Kyocera Corporation, Kyoto, Japan), which was fixed to a stainless steel stem by a 1/10 tapered cone. The alumina ceramics used for the femoral head contained 7% yttria for radio-opacity, and the average grain size of the ceramics was less than 7 μm . The average surface roughness of a new head was less than 0.04 μm of Ra (arithmetic mean of the absolute value of the measured profile height deviation as measured from the graphical center line) and its roundness recorded by the maximum radial peak-valley separation value was 1 μm or less. Polyethylene of the Bioceram component was machined from compression-

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Table 1 Demographic data for the retrieved components

Patient	Type of component	Examined components	Thickness of polyethylene (mm)	Duration in situ (years)	Side	Sex	Age (years)	Weight (kg)	Reason for removal
1	Bioceram	Cup, head	7	10.2	Right	Female	55	55	Cup loosening
2	Bioceram	Cup, head	9	11.4	Left	Male	45	68	Cup loosening
3	Bioceram	Cup, head	7	9.3	Right	Female	42	51	Cup loosening
4	Bioceram	Cup	7	12	Left	Female	53	65	Cup loosening
5	Bioceram	Cup	7	9.8	Left	Female	52	58	Cup loosening
6	Bioceram	Cup	7	10.8	Left	Female	50	50	Cup loosening*
7	Bioceram	Cup, head	9	13.6	Right	Male	46	55	Cup loosening
8	Bioceram	Cup	9	11.1	Left	Female	65	59	Cup loosening
9	Bioceram	Cup	8	13.7	Left	Female	51	55	Cup loosening
10	Bioceram	Cup	7	12.8	Right	Female	59	43	Cup loosening
11	Bioceram	Cup, head	9	13.8	Left	Female	51	52	Cup loosening
12	Bioceram	Cup	7	11	Left	Female	47	52	Cup loosening
13	Bioceram	Cup, head	8	17.1	Left	Female	64	40	Cup loosening
14	Bioceram	Cup, head	9	15.4	Right	Male	56	70	Cup loosening
15	Bioceram	Cup, head	8	16.2	Left	Female	44	60	Cup and stem loosening
16	Bioceram	Cup, head	7	16	Left	Female	55	45	Cup loosening
17	Bioceram	Cup, head	9	15.9	Left	Female	56	55	Cup loosening
18	Bioceram	Cup, head	7	15.7	Left	Female	52	55	Cup loosening
19	Bioceram	Cup, head	7	9.9	Right	Female	54	56	Cup and stem loosening
20	Bioceram	Head	—	15.5	Left	Female	50	50	Revision cup loosening*
21	Bioceram	Cup, head	8	14.5	Left	Female	47	51	Cup loosening
22	Bioceram	Cup, head	8	15.8	Left	Female	39	50	Cup loosening
23	Müller	Cup	6	15.8	Right	Female	60	63	Cup and stem loosening
24	Müller	Cup	6	11.1	Left	Female	63	51	Cup and stem loosening
25	Müller	Cup	6	15.6	Right	Female	54	43	Cup loosening
26	Müller	Cup	6	13.3	Right	Female	57	47	Cup loosening
27	Müller	Cup, head	9	14.3	Left	Female	56	63	Cup loosening
28	Charnley	Cup, head	10	10.4	Left	Female	54	43	Cup loosening
29	Charnley	Cup, head	9	22	Left	Female	42	60	Cup and stem loosening
30	Charnley	Cup, head	12	12.5	Left	Female	60	58	Cup and stem loosening
31	Charnley	Cup, head	9	15	Right	Female	60	55	Cup and stem loosening
32	Charnley	Cup, head	9	18.1	Left	Female	54	55	Cup and stem loosening
33	Charnley	Cup, head	9	16	Right	Female	51	54	Cup and stem loosening

* Case 6 and 20 were the same patient. This patient underwent isolated acetabular revision 10.8 years after primary total hip arthroplasty and acetabular re-revision with head exchange 15.5 years after primary total hip arthroplasty

Table 2 Demographic data of the patients undergoing revision surgery

	Type of component		
	Bioceram	Müller	Charnley
Number of hips	22	5	6
Age at initial operation (years)	52 (39–65)	58 (54–63)	54 (42–60)
Body weight (kg)	54.3 (40–70)	53.4 (43–63)	54.2 (43–60)
Duration in situ (years)	13.3 (9.3–17.1)	14.0 (11.1–15.8)	15.7 (10.4–22)
Values are means (range)			

molded sheets consolidated from GUR412 (Hostalen GUR, Hoechst AG, Frankfurt, Germany) and sterilized with ethylene oxide gas (Et-O).

The Müller component had a 32 mm diameter femoral head made of Co-Cr alloy and the Charnley component had a 22.25 mm diameter femoral head made of stainless steel. These two types of femoral components were monoblocked. Polyethylene of the Müller and Charnley components were machined from compression-molded sheets (RCH 1000, RCH-1000 C, 412GUR, Hoechst AG), and sterilized by gamma irradiation in air. Average thickness of polyethylene was 7.8 mm (range, 7 to 9 mm) in the Bioceram component, 6.6 mm (range, 6 to 9 mm) in the Müller component, and 9.7 mm (range, 9 to 12 mm) in the Charnley component (Table 1). There was no polyethylene with thickness less than 6 mm.

In general, the worn surface of the polyethylene could usually be distinguished by the presence of a distinct contour that was different from the original articulating contour [15]. The linear wear of retrieved polyethylene components was determined as the distance between the center of the original articulating contour and that of the secondary formed contour by the femoral head penetration. The linear wear was measured directly with the coordinate measuring machine (BHN305, Mitutoyo Corporation, Japan), and the volumetric wear was calculated according to Kabo's method [16] based on the following values: femoral head radius, polyethylene component radius, wear direction, and the linear wear of polyethylene.

Polyethylene quality was evaluated as the number of fusion defects per cubic millimeter, which was calculated by the number of defects on a thin slice cut by microtome from retrieved polyethyl-

ene components, divided by thickness of the slice. The worn surfaces of retrieved polyethylene components were observed using a scanning electron microscope (JSM-5410LV, NEC, Japan), and evaluated for scratches and embedded third body wear particles.

The surface of retrieved femoral heads was inspected for visible scratches. The modular head-neck junction was carefully inspected for fretting or corrosion in the Bioceram component. Surface roughness of the retrieved femoral head was measured with the contact profilometer (S-405, Kosaka Kenkyusho Corporation, Japan) with a head speed of 0.3 mm/s and a cutoff length of 0.80 mm. Measurement was done at two points: at the pole of the femoral head and at equatorial portion. At each point, surface roughness was measured on two lines perpendicular to each other. Roundness was measured using the roundness measuring instrument with a contact stylus (MODEL EC-1030A, Kosaka Kenkyusho Corporation, Japan) on a circle around the equator of the head and that tilted 20° from the equatorial plane. The surface of retrieved femoral heads was observed using scanning electron microscopy (SEM) and compared with a new head.

Statistical analysis was performed with the Mann-Whitney U test, one factor analysis of variance (one factor ANOVA), and the Bonferroni test. Difference was considered statistically significant when the *P*-value was less than 0.05.

Results

The average linear wear rate of polyethylene was greatest in the Bioceram component, but significant difference could not be found among the three types (Table 3). The volumetric wear rate of polyethylene was significantly greater in the Bioceram component (Bonferroni test, *P*<0.05).

Although the Müller component tended to have more fusion defects than the other two components, no significant difference was found among the three groups (Table 3). SEM revealed that the worn surfaces of polyethylene in the Bioceram component were smooth, but accompanied by some multidirectional fine scratches (Fig. 1). No third body wear particle was embedded in any polyethylene socket.

Fig. 1 Scanning electron microscopy (SEM) of the worn surface in the Bioceram component. Multidirectional fine scratches were observed

Average Ra values were lowest for the Bioceram alumina head regardless of site of measurement (Table 4). Average roundness of the Bioceram alumina heads was better than that of the metal heads. When all metal heads were taken together, significant differences were found both in surface roughness and roundness between alumina heads and metal heads (Mann-Whitney U test, *P*<0.05). SEM of the surface of the alumina heads did not reveal any obvious scratches, but identified some voids of about 2–10 µm in diameter, which were also observed on a new head (Fig. 2). The surface roughness and roundness of the retrieved alumina heads were similar to new alumina heads. The retrieved alumina heads maintained a polished appearance like that of a new head and showed no visible scratches. No visible fretting or corrosion was found during revision surgery at

Table 3 Wear and fusion defects of retrieved polyethylene components

	Bioceram	Müller	Charnley
Number of examined polyethylenes	21	5	6
Linear wear rate (mm/year)	0.19±0.084 (0.03–0.35)	0.10±0.028 (0.05–0.12)	0.16±0.074 (0.03–0.25)
Volumetric wear rate (mm ³ /year)	70.1±33.9(9.3–127.1)*	42.2±14.3(21.1–58.1)	38.0±17.3(6.4–54.7)
Fusion defect (/mm ³)	20.9±8.26 (6.3–32.9)	29.4±7.60 (21.1–39.6)	17.3±7.43 (3.0–24.0)

Values are means±standard deviation (range); *Difference was statistically significant (Bonferroni test *P*<0.05)

Table 4 Surface finishes of retrieved femoral heads

	Bioceram	Müller	Charnley
Number of examined femoral heads	15	1	6
Surface roughness (Ra, µm)			
Top	0.031 ±0.014 (0.01–0.04)	0.04	0.17±0.32 (0.04–1.52)
Equatorial portion	0.031 ±0.013 (0.01–0.04)	0.12	0.040±0 (0.04–0.12)
Roundness (kc m)			
Equator of the head	0.37±0.23 (0.13–0.90)	5.62	2.40±1.99 (0.91–5.62)
20° tilted from equator	0.37±0.23 (0.20–1.09)	7.8	1.79±1.70 (0.60–7.80)

Values are means±standard deviation (range)

Fig. 2 **A** Scanning electron microscopy (SEM) of the retrieved alumina head. No scratch was found on the surface. A few voids (about 2–10 µm in diameter) and grain boundaries are present. **B** SEM of the new alumina head. Similar voids seen in the retrieved head are present

the modular-head neck junction in the Bioceram component.

Discussion

Polyethylene wear is affected by multiple factors. Accumulation of a number of wear studies suggest that patient-related variables such as age [9, 19], daily activity [9]; implant-related factors such as surface finish [36, 37], materials [27], diameters of femoral head [7], base resins [2, 13], fabrication methods [1], fusion defects [35, 40], thickness [3, 5, 18], sterilization of polyethylene [24, 32, 38, 39], third body wear [12, 33] and lubrication [28] affect polyethylene wear. Because polyethylene wear in vivo is actually affected by all of these variables, the mechanism of in vivo wear has not been defined. Therefore, we evaluated the condition of retrieved implants, which are considered to well reflect in vivo wear. Of these variables, we focused on the polyethylene and femoral head surface quality.

Alumina ceramic heads have been considered as one solution to reducing polyethylene wear. The theoretical advantages of alumina ceramic heads are improved lubrication due to their hydrophilic surface [8] and maintenance of the initial surface finish for longer periods in vivo [25, 33]. In vitro wear studies support this wear performance of alumina ceramic heads [26, 30], whereas radiographic studies are not always in agreement [31, 34].

The present study showed that retrieved alumina heads maintained better surface quality demonstrated as surface roughness (Ra) and roundness than metal heads after more than 9 years in vivo. These results were consistent with previous reports [25, 33]. However, the Bioceram component showed significantly greater volumet-

ric wear rate of the polyethylene than the other types. To explain this paradoxical result we have considered 4 factors: polyethylene quality, sterilization methods of polyethylene, inadequate expression of surface finish of femoral heads and third body wear.

Polyethylene quality was evaluated as fusion defects. These have been shown to be related with increased polyethylene wear damages [35, 40]. However, the fusion defects in the three components were similar, which indicates that polyethylene quality evaluated by fusion defects apparently is not a causal factor.

Sterilization methods have a great influence on the mechanical property and wear performance of polyethylene. Polyethylene sockets of the Bioceram component were sterilized with Et-O, while those of the Müller and Charnley components were sterilized by gamma irradiation in air. Et-O sterilization is easy to do and does not cause oxidative degradation. On the other hand, sterilization by gamma irradiation in air causes the potential risk of oxidative degradation, but it causes cross-linking, which improves the wear-resistant property of polyethylene [32]. McKellop et al. [24], using a hip simulator, recently showed that the wear of polyethylene sterilized with Et-O was significantly greater than that sterilized by gamma irradiation in air. Although this is an in vitro study the result suggests that Et-O sterilization might be one reason for the increase in polyethylene wear of the Bioceram component.

With regard to the surface finish of femoral heads, Wang et al. [36] reported that a counterface with a greater Ra value showed greater polyethylene wear when using a hip joint simulator. On the other hand, Fisher et al. [11] reported that a small scratch that had not been detected by Ra caused an increase in polyethylene wear according to a pin-on-disc wear tester. Elfick et al. [10] in an analysis of 42 retrieved femoral heads found that surface finish did not correlate with the polyethylene wear rate. These results support the theory that a femoral head with a lower Ra value does not always reduce polyethylene wear in vivo.

Sychterz et al. [33] by examining 24 retrieved femoral heads at autopsy found that the surface finish did not

correlate with polyethylene wear. They found that the polyethylene wear rate for cups with embedded particle debris in the liner was significantly greater than that for cups without such particles. They concluded therefore that third body wear mechanism is very important. Jasty et al. [14] suggested that the modular head neck junction would be a source of third body wear particle generation based on the finding that the femoral heads of modular total hip prostheses showed significantly greater surface damage than those of monoblock types. In the present study, we failed to detect any embedded particles. Neither could we find any corrosion or fretting macroscopically at the modular head-neck junction. However, multidirectional scratches on the worn surface of the Bioceram component indicated the presence of third body wear. We suppose that the susceptibility to third body wear is greater in an alumina polyethylene bearing than in a metal polyethylene bearing couple. This might be a causal factor for the increase in polyethylene wear seen in Bioceram components.

The present study has two limitations. The thickness of polyethylene was not similar among the groups and the components analyzed in the present study were all removed because of failure of fixation.

In conclusion, maintaining good surface roughness of the femoral heads during in vivo service is necessary, but not sufficient to reduce polyethylene wear. We should pay attention not only to improvements of the counterface roughness and polyethylene quality but also to sterilization methods of polyethylene and elimination of third body wear.

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