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Quantification of third-body damage and its effect on UHMWPE wear with different types of femoral head

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We examined stainless-steel, cobalt-chrome, titanium and alumina and zirconia ceramic femoral heads retrieved at revision surgery. All the heads had articulated against ultra-high-molecular-weight-polyethylene (UHMWPE) acetabular cups. We studied the simulation of third-body damage and the wear of UHMWPE against the various materials used for the heads. The surfaces of the retrieved heads were analysed using a two-dimensional contacting profilometer. Third-body damage was characterised by the mean height of the scratches above the mean line (R_{pm}).

The alumina ceramic and zirconia ceramic retrieved heads were found to have significantly less damage. In laboratory studies the ceramics were also more resistant to simulated third-body damage than the metal alloys. We studied the wear of UHMWPE against the damaged counterfaces in simple configuration tests. The damaged ceramics produced less polyethylene wear than the damaged metal counterfaces. The wear factor of UHMWPE against the damaged materials was dependent on the amount of damage to the counterface (R_p). Our study has shown the benefit of using the harder and more damage-resistant ceramic materials for femoral heads.

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Although there has been gradual improvement in the materials, design and surgical techniques for total hip replacement (THR) over the last decade, many problems still remain. In particular, for the long-term success of THR, factors which cause high rates of wear must be identified in order to reduce the amount of wear debris produced. The clinical importance of these problems has increased since THR has become available to younger and more active patients who are themselves demanding a better quality of life. Implants now require to have a low coefficient of friction, resistance to third-body damage and wear, the generation of small amounts of wear debris, and low cellular reactions to such wear debris.

Many studies, including wear tests, scratch tests, measurements of explanted prostheses and analysis of wear debris, have been performed in order to understand the mechanism of wear of ultra-high-molecular-weight polyethylene (UHMWPE) in implants. Polyethylene debris produces a foreign-body-connective-tissue reaction in the form of osteolysis and the formation of granuloma along the implant-bone interface. This reaction often progresses to late aseptic loosening.[1-3] The surface topography or roughness of the counterface which rubs against the UHMWPE is one of the most important factors controlling the rate of wear of the polymer.[4] In laboratory tests, a single scratch 2 μm deep on a metal counterface has been shown to produce a dramatic increase in the wear of UHMWPE.[5] The roughening of the femoral counterface can also increase the number of wear particles generated. Clinically, damage to metal femoral heads can be caused by third bodies: bone-cement particles,[6,7] bone particles[8] and metal debris.[9] In laboratory simulator studies little difference has been found between the wear of acetabular cups articulating against alumina ceramic or cobalt-chrome femoral heads,[10] but clinical studies have shown a reduced amount of wear with alumina ceramic compared with metal heads.[11-13] A comparison, however, of both third-body

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Table I. Details of the implants

Material	Number in sample	Mean implantation time (yr)	Fixation*	Reason for revision	Mean age of patients (yr)
Stainless-steel	10	14.5	C	Loosening	55.3
Cobalt-chrome	10	14.4	C	Loosening	69.9
Titanium	7	-	C/UC	-	-
Alumina ceramic	10	4.8	C/UC	Loosening/dislocation/infection	50.7
Zirconia ceramic	8	3.4	C/UC	Loosening/dislocation/infection	-

* C, cemented; UC, uncemented

damage and wear in ceramic and metal femoral heads has not been previously reported.

We have therefore examined and quantified damage to the femoral head and the wear of UHMWPE against femoral-head materials on which third-body damage had been simulated in stainless-steel, cobalt-chrome, titanium, alumina ceramic and zirconia ceramic femoral heads retrieved at revision surgery.

Materials and Methods

Study of explanted femoral heads. We analysed ten Charnley stainless-steel, ten cobalt-chrome, seven titanium alloy, ten alumina ceramic and eight zirconia femoral heads (Table I). They were measured using a form Talysurf (Rank Taylor Hobson, Leicester, UK), which is a contacting two-dimensional profilometer, in four fixed positions, two traces on the articular surface and two on the non-articular area. Areas of macroscopic damage visible to the naked eye were also measured. Figure 1 shows the locations for measurement. Care was taken not to include damage by surgical instruments in the measurements. The length of each trace was 5.6 mm. For stainless-steel, titanium, alumina ceramic and zirconia ceramic heads a 0.8 mm cut-off with an ISO 2CR filter was applied and for cobalt-chrome heads a 0.25 mm cut-off with an ISO 2CR filter since some waviness still remained when a 0.8 mm cut-off was used. The mean height of the scratches above the mean line R_{pm} was used to characterise the third-body damage. R_{pm} is the mean of the R_p values obtained for each sampling length of an assessment (Fig. 2). R_p and R_{pm} were selected for this analysis since previous studies[4] have shown that they have a marked effect on the wear of UHMWPE.

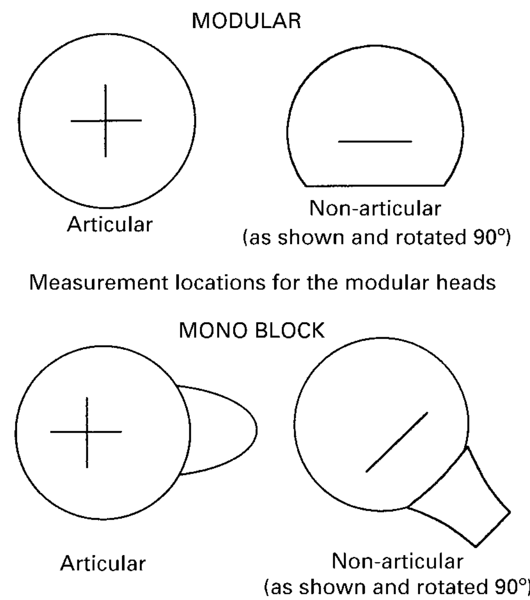

Fig. 1

Locations for measurement on the explanted femoral heads.

Simulation of third-body damage and polyethylene wear. Stainless-steel, cobalt-chrome alloy, alumina ceramic and zirconia ceramic plates were highly polished to a surface roughness (R_a) better than 0.01 μm. Third-body scratches were simulated on the plates using a diamond stylus with a load of 0.4 N in the range of R_p of 0.1 μm to

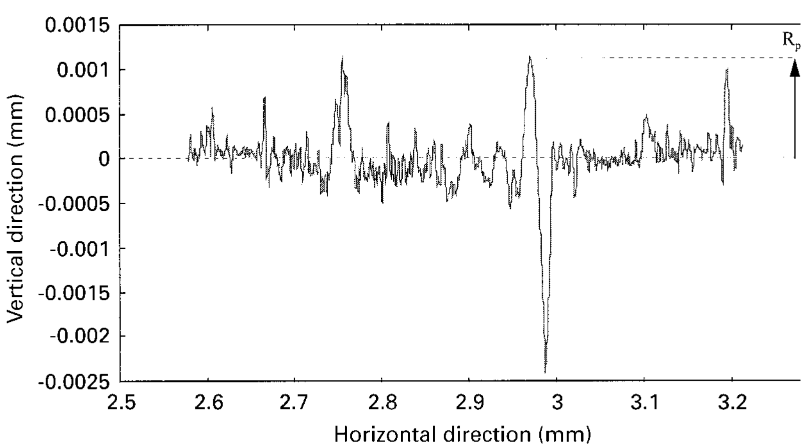

Fig. 2

A form Talysurf trace showing R_p and a typical scratch geometry.

1.0 μm similar to those found on explanted femoral heads. The scratches were characterised by the mean height of the R_p of the lips above the mean surface line using the Talysurf.

We studied wear of UHMWPE by sliding the polymer against stainless-steel, cobalt-chrome alloy, alumina ceramic and zirconia ceramic plates on which third-body damage had been simulated. Each plate had eight equal scratches 5 mm apart. Cylindrical polyethylene pins were machined from an extruded UHMWPE bar (GUR 415). They were not irradiated. Each pin was 12 mm long, having a truncated cone approximately 5 mm in diameter at one end which was microtomed. The wear tests were carried out using a six-station pin-on-plate reciprocating machine which allowed movement along one axis. The lubricant used in the tests was 25% bovine serum diluted with 0.1% sodium azide solution. The reciprocating speed was 2.5 Hz with a stroke length of 35 mm. Although this gives a sliding velocity which is higher than physiological velocities, this does not affect the rates of wear.[14] The applied load was 160 N for each pin, corresponding to a nominal stress of 8 MPa. Each test was carried out for 24 hours on the metal plates, giving a sliding distance of 15 Km, and for 48 hours on the ceramic plates, giving a sliding distance of 30 Km. Six independent measurements of wear were made for each counterface material. A longer sliding distance was used for the ceramic plates in order to produce a larger wear volume which was necessary to measure accurately the volume loss of the UHMWPE. Control pins were placed in a bath containing the bovine serum and the sodium azide and their change in weight measured to take account of fluid uptake; this was found to be small. Syringe drivers were used to add 0.1% sodium azide to the lubricant to keep it topped up during the test. The UHMWPE pins were weighed before and after the wear tests and before being weighed were allowed to stabilise in a temperature-controlled room for 24 hours. The wear was expressed as a wear factor (K) mm^3/Nm, which is the wear volume (V) mm^3 divided by the load (W) N and the sliding distance (X) m. The mean value for the wear factors was compared by a one-way analysis of variance. Statistical significance was taken at the 95% confidence interval (CI).

Results

Study of explanted femoral heads. Table II gives the mean R_{pm} for the explanted femoral heads. When no macroscopically damaged area was observed, the data of the trace which had the larger R_{pm} on the articular area were used for analysis. Figure 2 shows a trace from the Talysurf with a typical scratch geometry.

The mean R_{pm} for the alumina ceramic heads was the smallest for all three areas: articular, non-articular and damaged. For the alumina and zirconia ceramic heads it was less than that for the metal alloy femoral heads which was statistically significant (Student's *t*-test, $p < 0.01$). None of the alumina or zirconia ceramic heads had macroscopic damage. The mean R_{pm} for the stainless-steel and cobalt-chrome alloy heads was greater for the area of macroscopic damage than for the articular and non-articular areas and for the titanium-alloy heads it was the largest in all three areas. The articular areas on the titanium-alloy heads were worn and damaged uniformly, and the boundary between the articular and the non-articular areas was clear.

Table II. Mean R_{pm} (μm) on the three different surfaces for the explanted femoral heads (0.8 mm cut-off was applied for stainless-steel, titanium and alumina and zirconia heads and 0.25 mm cut-off for cobalt-chrome heads)

Material	Articular area	Non-articular area	Damaged area
Stainless-steel	0.068	0.059	0.400
Cobalt-chrome	0.056	0.076	0.446
Titanium	0.241	0.130	0.556
Alumina ceramic	0.018	0.016	0.023
Zirconia ceramic	0.035	0.036	0.043

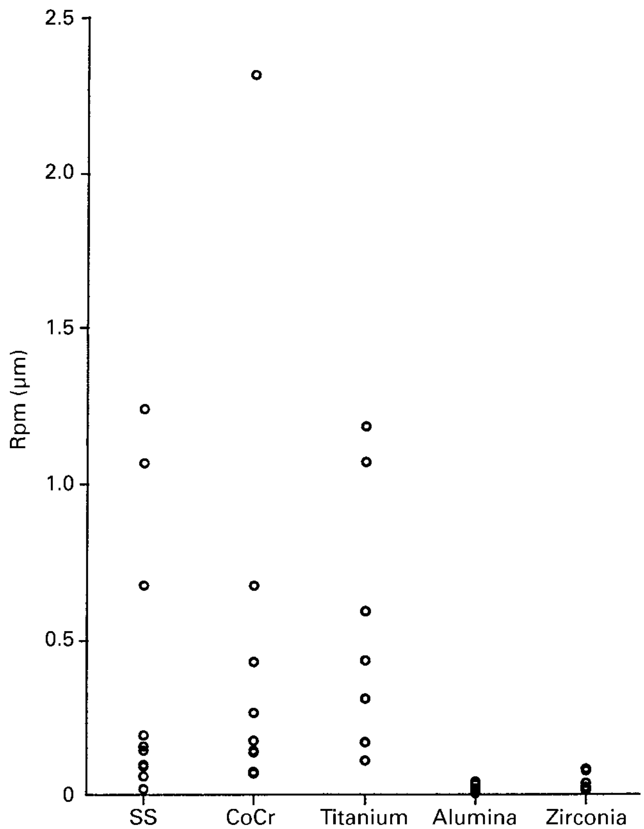

Fig. 3

The distribution of R_{pm} of the damaged areas on the femoral heads.

Figure 3 shows the distribution of R_{pm} for the damaged areas of the femoral heads. The R_{pm} for all the metal femoral heads showed wide variations and different degrees of third-body damage. All values of R_{pm} for the ceramic heads were less than 0.1 μm.

Simulation of third-body damage and wear of polyethylene. The mean R_p for simulated scratches was in ascending order of alumina ceramic, zirconia ceramic,

Table III. Mean R_p (μm) for the simulated scratches on the different types of material

Material	Mean R_p
Stainless-steel	1.01
Cobalt-chrome	0.39
Alumina ceramic	0.05
Zirconia ceramic	0.06

cobalt-chrome alloy and stainless steel. The mean R_p for the alumina and zirconia ceramic plates was significantly lower than that for the metal plates (Student's *t*-test, $p < 0.01$). The mean R_p for cobalt-chrome alloy was less than that for stainless-steel. Table III shows the mean value for the R_p for the scratches on the four different counterfaces.

Figure 4 shows the wear factors of the UHMWPE against the damaged counterfaces of the different materials. The stainless-steel counterfaces produced the greatest wear factor of the UHMWPE, the mean being 45.0×10^{-9} mm^3/Nm, which is about three times greater than that for the cobalt-chrome counterfaces and five times greater than for the alumina and zirconia ceramic counterfaces. The mean wear factor for the cobalt-chrome counterface was 16.8×10^{-9} mm^3/Nm, for the zirconia ceramic counterface 9.9×10^{-9} mm^3/Nm and for the alumina ceramic counterface 8.6×10^{-9} mm^3/Nm. The ceramics produced the lowest wear factors. There were statistically significant differences between the wear factors for UHMWPE sliding on the stainless-steel and on the other counterfaces. There was also a statistically significant difference between the wear factors for the UHMWPE sliding on the cobalt-chrome and on the alumina ceramic.

Figure 5 shows the variation of the UHMWPE wear factor with counterface R_p. The wear factors for the polyethylene pins sliding on the damaged counterfaces were primarily dependent on the height of the lip of scratch lips on the different materials. The wear factor increased with the increase in R_p. The lowest wear was found on the alumina ceramic with the lowest R_p; this was significantly less than the wear factors found on the scratched metal counterfaces.

Discussion

Metal heads on UHMWPE acetabular cups are the most popular combination for joint prostheses, and have been used more than any other implant since Charnley introduced UHMWPE for the acetabular component in 1962. Polyethylene wear, however, remains the major source of debris in THR. While much attention is currently being focused on different types of polyethylene and different sterilisation methods in attempts to reduce the volumetric wear rates of polyethylene acetabular cups, much less consideration is being given to the femoral head counterface, which can have a marked influence on the wear of

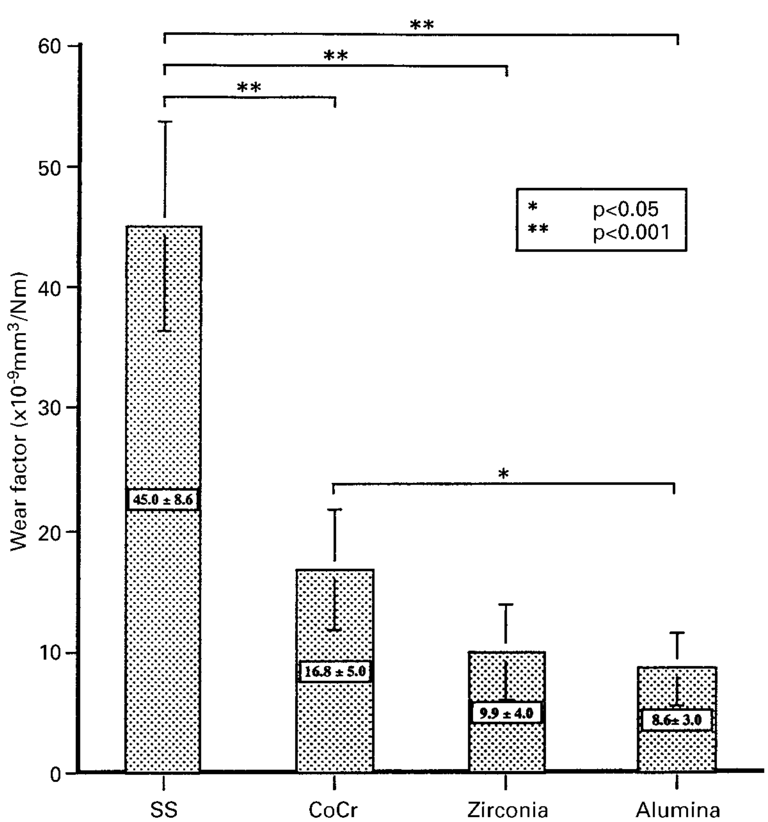

Fig. 4

Wear factor of UHMWPE against different counterface materials (mean ± 95% CI).

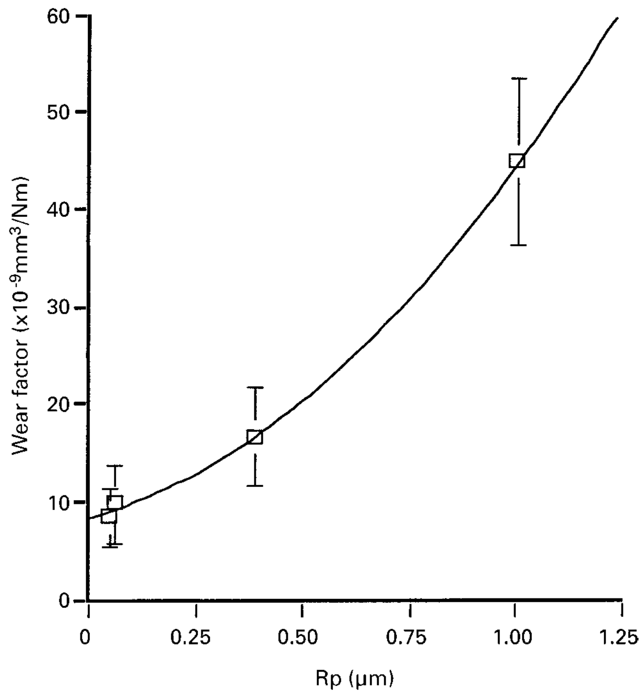

Fig. 5

Variation of UHMWPE wear factor with counterface R_p (mean ± 95% CI).

polyethylene. Although alumina ceramic femoral heads have been available for over 20 years, concerns about higher costs and reduced fracture toughness have restricted their use in many parts of the world.

The in vivo studies of the explanted ceramic heads showed that there was much less damage produced by third bodies than in metal heads. It should be noted, however, that the mean lifetime of the ceramic heads is less than that of the metal heads. All the stainless-steel and cobalt-chrome heads were implanted using bone cement, but some ceramic heads had no cement. In addition, the reasons for revision were different for the metal and ceramic heads.

Because the profiles of the cobalt-chrome heads showed waviness with a 0.8 mm cut-off, a smaller cut-off of 0.25 mm was used for these. With 0.8 mm the mean R_{pm} cut-off was 0.095 for articular and 0.119 for non-articular areas, but with 0.25 mm it was 0.056 and 0.076, respectively. It is very important to use the appropriate cut-off for measuring surface roughness in order to differentiate roughness from waviness.

The pin-on-plate wear tests used in our study cannot replicate all the tribological conditions found in the artificial hip. For example, there is no simulation of real-time degradation of UHMWPE, a multidirectional friction force and time-dependent loading, all of which can accelerate the wear of UHMWPE. As a result the wear in these simplified simulations is often lower than is found clinically. The pin-on-plate wear tests are particularly useful, however, since they can isolate a single tribological variable such as in this case the different scratch geometries on the counterfaces.

The most important observation to emerge from our study is the dependence of the polyethylene wear on the height of the scratch R_p or R_{pm}. It is not possible to predict directly relative clinical wear rates from simple configuration wear tests since in vivo many other tribological factors can accelerate wear, thus reducing the net effect of counterface damage on polyethylene wear. Some investigators, however, have reported that clinically ceramic heads significantly reduce polyethylene wear in hip prostheses. Schuller and Marti[12] found that the mean annual polyethylene wear against ceramic heads was 0.03 mm as compared with 0.10 mm for metal heads. In all cases the head size was 32 mm and the prostheses were implanted with bone cement. Oonishi et al[11] also reported a mean annual wear against ceramic of 0.10 mm as compared with 0.25 mm for stainless-steel. In all their cases the head size was 28 mm and the prostheses were implanted with bone cement. Wroblewski et al[13] found that alumina ceramic heads of 22.225 mm diameter with cross-linked polyethylene acetabular cups gave a good clinical performance. The mean annual polyethylene wear rate was 0.022 mm in that combination.

Recent retrieval studies[15,16] have shown a significant increase in the wear volume and the number of wear particles in metal femoral heads with high damage of R_{pm}. The retrieved heads were divided into low damage and high damage groups. The mean R_{pm} in the group with low damage was 0.07 ± 0.01 μm and in that with high damage 1.52 ± 0.42 μm. The linear wear rate was 0.12 ± 0.3 mm/year for the group with low damage and 0.22 ± 0.03 mm/year for that with high damage. The mean volumetric wear rate and number of particles were 40 ± 10 mm^3 and 297 ± 84 $\times 10^9$ with low damage and 80 ± 10 mm^3 and 577 ± 100 $\times 10^9$, respectively, with high damage.

Hailey et al[17] also reported that rough counterfaces produced many micron-sized particles and that these were fewer with smooth counterfaces. This indicated that increasing the counterface roughness increased wear volume and also the number of particles produced.

Analysis of the comparative surface damage of stainless-steel and cobalt-chrome alloy heads is not as clear. The laboratory studies showed a lower R_p and less polyethylene wear with the cobalt-chrome alloy. The amounts of damage found clinically, however, in the two groups were similar. There are two possible explanations. If the clinical damage had been caused by third-body metal particles from the stem, a difference might not necessarily be seen since both scratches were produced by particles of similar hardness to the head material. Alternatively, the lip thrown up by the scratches on the stainless steel may have been worn down by the polyethylene in vivo. Thus, the R_p of an explant could be less than that during the clinical lifetime.

There is a clear conclusion to be drawn from our study. Alumina and zirconia ceramics are more resistant to simulated third-body damage than metal alloys and produce less polyethylene wear in vivo in tests of simulated third-body damage. Clinically, they showed less third-body damage (R_{pm}) than metal heads and thus it can be predicted that these ceramics have the potential to produce lower long-term wear rates of the polyethylene acetabular cup.

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