Tribological and material analyses of retrieved alumina and zirconia ceramic heads correlated with polyethylene wear after total hip replacement

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It has been suggested that the wear of ultra-high molecular weight polyethylene (UHMWPE) in total hip replacement is substantially reduced when the femoral head is ceramic rather than metal. However, studies of alumina and zirconia ceramic femoral heads on the penetration of an UHMWPE liner in vivo have given conflicting results.

The purpose of this study was to examine the surface characteristics of 30 alumina and 24 zirconia ceramic femoral heads and to identify any phase transformation in the zirconia heads. We also studied the penetration rate of alumina and zirconia heads into contemporary UHMWPE liners. The alumina heads had been implanted for a mean of 11.3 years (8.1 to 16.2) and zirconia heads for a mean of 9.8 years (7.5 to 15).

The mean surface roughness values of the explanted alumina heads (Ra 40.12 nm and Rpm 578.34 nm) were similar to those for the explanted zirconia heads (Ra 36.21 nm and Rpm 607.34 nm). The mean value of the monoclinic phase of two control zirconia heads was 1% (0.8% to 1.5%) and 1.2% (0.9% to 1.3%), respectively. The mean value of the monoclinic phase of 24 explanted zirconia heads was 7.3% (1% to 26%).

In the alumina group, the mean linear penetration rate of the UMWPE liner was 0.10 mm/yr (0.09 to 0.12) in hips with low Ra and Rpm values (13.22 nm and 85.91 nm, respectively). The mean linear penetration rate of the UHMWPE liner was 0.13 mm/yr (0.07 to 0.23) in hips with high Ra and Rpm values (198.72 nm and 1329 nm, respectively). This difference was significant (p = 0.041).

In the zirconia head group, the mean linear penetration rate of the UHMWPE liner was 0.09 mm/yr (0.07 to 0.14) in hips with low Ra and Rpm values (12.78 nm and 92.99 nm, respectively). The mean linear penetration rate of the UHMWPE liner was 0.12 mm/yr (0.08 to 0.22) in hips with high Ra and Rpm values (199.21 nm and 1381 nm, respectively). This difference was significant (p = 0.039).

The explanted zirconia heads which had a minimal phase transformation had similar surface roughness and a similar penetration rate of UHMWPE liner as the explanted alumina head.

It has been suggested that the wear rate of ultra-high molecular weight polyethylene (UHMWPE) in total hip replacement (THR) is substantially reduced when the femoral head is ceramic rather than metal (Co-Cr-Mo alloy). Although alumina has improved in quality and alumina ceramic femoral heads have been implanted for more than 40 years, fractures of alumina ceramic femoral heads continue to occur. In an attempt to address this problem, zirconia ceramic femoral heads were introduced approximately 20 years ago. These have been shown to be two to three times stronger than alumina heads.

Cuckler et al first reported that a zirconia head had a lower penetration rate than a cobalt-chrome or alumina head when used with a UHMWPE liner. However, zirconia has a chequered history. Some studies have shown a high penetration rate of UHMWPE liners by zirconia heads. This is ascribed to surface transformation from the metastable tetragonal phase to the monoclinic phase. The volume increase that occurs with this phase change causes particles to rise from the surface, thereby increasing surface roughness and polyethylene wear.

This study aimed to find out whether the surface characteristics of explanted alumina and zirconia femoral heads were similar, whether zirconia femoral heads would undergo phase transformation, and whether a zirconia head had a lower penetration rate than an alumina head when used with a UHMWPE liner.
Materials and Methods
The study was approved by our institutional review board, and all patients provided informed consent.

We examined 30 alumina heads (Biolox forte; Ceramtec AG, Plochingen, Germany) and 24 zirconia heads (Prozyr; Saint Gobain, Vincennex Cedex, France) retrieved at revision surgery. The primary diagnosis did not differ between the two groups. The demographics of these groups and the implants used are shown in Table I.

The activity level of the patients between their primary and revision THR was assessed using the activity score described by Tegner and Lysholm.10 An activity grading scale, in which work and sports activities are graded numerically, was constructed as a complement to the functional score. The patients were given a score according to the activities in which they engaged in daily life. The score ranged from 0 for a hip-related disability to ten for participation in competitive sports at a national level. The majority of patients were quite active despite the usual cautions to avoid activities involving impact after THR. Each patient had an activity score of 5 or 6 points before revision, indicating participation in strenuous farm work (5 points) or participation in tennis (6 points).

Analysis of retrieved femoral heads. The surface characteristics of the 54 explanted ceramic femoral heads were evaluated by two different methods: interferometry (Wyko RST 500 interferometer; Wyko, Tucson, Arizona), and environmental scanning electron microscopy. Phase analysis was performed by X-ray diffraction for the 24 zirconia ceramic heads.

The interferometry measurements were undertaken at two different magnifications using 20 × and 40 × lenses. The areas of analysis were 125 μm × 125 μm and 64 μm × 64 μm, respectively. At each magnification, six measurements were made of the weight-bearing (pole) areas and non-weight-bearing areas of the ceramic heads. The unworn/non-weight-bearing and worn/weight-bearing areas of the heads were defined by marking the components at revision. The results are presented in Ra and Rpm. The parameter Ra is defined as the mathematical average of all deviations (peaks and valleys) from the mean line of the surface profile. The parameter Rpm (the mean levelling depth) is defined as the distance between the mean line and a line parallel to it which passes through the highest point. The intrinsic errors of the measurement of Ra and Rpm are ± 0.017 nm and ± 0.162 nm, respectively. The measurement resolution of the interferometer is < 1 Å in phase shift interferometry mode and < 1 nm in vertical shift interferometry mode. Therefore, the phase shift interferometry mode is more accurate for highly-polished surfaces. The vertical shift interferometry mode is appropriate for surfaces that are rough, or highly contoured, or that have sharp-peaked surfaces typically > 0.6 μm in height.
...The roughness values of the non-weight-bearing surface of each femoral head were used to estimate the roughness values of each femoral head before implantation. In addition, two alumina heads and two zirconia heads which had not been implanted were analysed to confirm that the non-weight-bearing surface of the retrieved specimens reflected the surface roughness of a ceramic head before implantation and thus were appropriate to use as controls.

Further surface analysis was performed using a Camscan 4 environmental scanning electron microscope (University of Leeds, Leeds, United Kingdom) by two scientists who had no knowledge of the clinical and experimental results. Secondary and backscattered electron microscopic images were reviewed at various magnifications (particularly at ×250 and ×8000) in an attempt to assess the pits and scratches on the head surfaces.

The 24 zirconia ceramic femoral heads were analysed using a Philips-X’pert, Modular Powder Diffractometer (Philips, Eindhoven, The Netherlands), which can accommodate these relatively large samples. This instrument was chosen for its sensitivity and excellent resolution. The sample was positioned on the optical axis of the instrument by means of a dial gauge. Whole ball heads were differentiated between weight-bearing and non-weight-bearing areas which were defined by marking the components at revision.

The crystalline phases present in the zirconia ceramic femoral heads were identified by comparison with the Powder Diffraction File (PDF) from the International Center for Diffraction Data (ICDD) version 49. The database contains X-ray diffraction patterns (fingerprints) taken from pure materials. It is the most extensive powder diffraction (XRD) database in the world and is used by almost all practitioners.

The peak heights were measured directly from the diffraction patterns. Peaks from the XRD output were compared with library controls and a ratio of the peak strength (area under the peak) was used to calculate tetragonal to monoclinic ratios. The units are in millimol percent and are derived by taking the ratio of tetragonal to monoclinic peak areas in XRD and comparing that to a known library control of either 100% monoclinic or 100% tetragonal content in millimol percent units.

A stereoscopic zoom microscope (Nikon, Melville, New York) was used to examine the gross appearance of UHMWPE liners for evidence of embedded particle debris corresponding to each femoral head. The evidence for particle embedding was examined qualitatively by a research associate who had no knowledge of the clinical and experimental results. The nature of the embedded debris was determined.

**Radiological analysis.** The radiological criteria for loosening of a cementless acetabular component were radiolucent lines that initially appeared after two years; progression of radiolucent lines after two years; radiolucent lines in all three zones of DeLee and Charnley; radiolucent lines measuring ≥ 2 mm in any zone; and component migration. Definite loosening of a cementless femoral component was recorded if there was a progressive axial subsidence of > 3 mm, or shift into valgus or varus. A cementless femoral component was considered to be possibly loose when there was a complete radiolucent line surrounding the entire porous-coated surface on both the anteroposterior and lateral radiographs. Definite loosening of the cemented femoral component was recorded if there was a progressive axial subsidence of > 3 mm, a shift into valgus or varus, or a complete radiolucent line < 2 mm wide in all zones of Gruen, McNeice and Amstutz and/or cement mantle fracture on both the anteroposterior and lateral radiographs.

Radiographs were also examined for evidence of osteolysis. Acetabular osteolysis was defined as an area of expansive bone loss that originated at the bone-implant interface and extended into the pelvis. Femoral osteolysis was defined as an area of endosteal, intracortical, or cancellous bone loss that were scalloped or had the appearance of destruction of bone rather than disuse osteopenia. A radiolucent zone that was linear but > 2 mm wide was also deemed to be osteolysis.

We measured the linear penetration of the UHMWPE liner radiologically by determining the migration of the centre of the femoral head relative to that of the acetabular component, according to the computer-aided technique of Kim et al. The 95% confidence interval (CI) was considered a measure of reproducibility. Intra-observer error was SD 0.039 mm.

We compared the radiological measurements with direct measurements of all 54 acetabular components to validate this wear-measurement technique. Linear wear was measured directly from the retrieved UHMWPE liners using a three-dimensional coordinate measuring device (BHN 305; Mitutoyo, Tokyo, Japan). Validation testing revealed that the device tended to underestimate the true amount of femoral head penetration by a mean factor of 0.06 mm (0.03 to 0.09) in all 54 hips. The radiological measurements of femoral head penetration were thought to be reproducible.

**Statistics.** Student’s t-test was used to determine the possible correlations between the rate of femoral head penetration and several specific variables: patient age, gender, and activity level; duration of implantation; type of head, and phase transformation of zirconia heads. Linear regression analysis was used to investigate any relationship between the surface roughness values and the patient’s age, gender, weight, and activity level, the duration of implantation and type of head and phase transformation of zirconia heads. Wilcoxon’s rank-sum test was used to determine any statistical difference in surface roughness between heads articulating with UHMWPE liners with or without embedded debris. A p-value < 0.05 was considered significant.

**Results.**

**Analysis of retrieved femoral heads.** The surface characteristics of the explanted alumina and zirconia ceramic femoral heads were similar. The surface roughness values for
the non-weight-bearing surfaces of the alumina and zirconia heads compared well with the roughness values for the four control heads. The mean Ra and Rpm values of the control alumina heads were similar to those of the non-weight-bearing surface of the 30 explanted alumina heads (Ra 7.69 nm (2.23 to 26.75); Rpm 75.89 nm (21.33 to 263.64)). The mean Ra and Rpm values of the control zirconia heads were similar to those for the non-weight-bearing surface of the 24 explanted zirconia heads (Ra 6.78 nm (2.67 to 27.89); Rpm 69.98 nm (22.44 to 271.34)). The mean Ra and Rpm values for the weight-bearing area of the 30 explanted alumina heads were 40.12 nm (13.22 to 198.72) and 578.34 nm (85.91 to 1329), respectively. The Ra values for the weight-bearing surface of two alumina ceramic heads that had dislocated repeatedly were 153.32 nm and 193.92 nm, respectively and the Rpm values for the weight-bearing surface were 1913.15 nm and 877.34 nm, respectively. The mean Ra and Rpm values for the weight-bearing surface of the 24 implanted zirconia ceramic heads were 36.21 nm (12.78 to 199.21) and 607.34 nm (92.99 to 1381), respectively. The differences in roughness values between the alumina and zirconia heads were not significant (p = 0.102), irrespective of magnification (Table II).

The mean surface roughness values for the weight-bearing surfaces of the 18 alumina heads without third-body debris embedded in the corresponding UHMWPE liner (Ra 38.26 nm, Rpm 567.18 nm) were lower than those for the 12 alumina heads associated with embedded debris (Ra 168.27 nm, Rpm 1132.77 nm). The differences in roughness values between the two groups were significant (p = 0.03 for both). However, no correlation was found with the numbers available, between the roughness values of the alumina heads and the following attributes: age, gender, weight, and activity level of the patient; duration of implantation; and type of femoral and acetabular component (p > 0.05 according to linear regression analysis).

Phase analysis of the 24 explanted zirconia heads consistently gave lower values for the amount of monoclinic phase (Fig. 1). The mean value of the monoclinic phase of the two control zirconia heads was 1% (0.8% to 1.5%) and 1.2% (0.9% to 1.3%), respectively. The mean value of monoclinic phase in the 24 explanted zirconia heads was 7.3% (1% to 26%) and that of tetragonal phase was 92.8% (74% to 99%). The mean value of the monoclinic phase of the 24 explanted zirconia heads was 7.7% in the weight-bearing areas (1% to 25%) and 6.8% (1% to 26%) in the non-weight-bearing areas. The mean value of the tetragonal phase in the weight-bearing areas was 92.3% (75% to 99%) and 93.2% (74% to 99%) in the non-weight-bearing areas.

The mean surface roughness values for the weight-bearing areas in the 15 zirconia heads without third-body debris embedded in the corresponding UHMWPE liner (Ra 42.67 nm, Rpm 619.29 nm) were lower than those for the nine zirconia heads associated with embedded debris (Ra 181.33 nm, Rpm 1627.44 nm). The differences in roughness values between the two groups were significant (p = 0.02 for both). However, no correlation was found with the numbers available, between roughness values of the zirconia heads and the following attributes: age, gender, weight, and activity level of the patients; duration of implantation; type of femoral and acetabular component; and amounts of monoclinic zirconia.

Environmental scanning electron microscopic evaluation of the alumina and zirconia heads revealed small pits and scratches on the weight-bearing surfaces of every ceramic femoral head. There was no significant difference in the incidence of these between the alumina and zirconia heads (p = 0.189) (Fig. 2). No pits or scratches were found on the non-weight-bearing surfaces.

Gross examination of the UHMWPE liner revealed evidence of embedded particle debris in 12 of the 30 liners (40%) in the alumina head group and nine of 24 liners (38%) in the zirconia head group. In the alumina group, the number of embedded particles was between two and five and in the zirconia group between two and six. In most cases of both groups, the embedded debris consisted of small non-metallic particles. These could not, however, be positively identified.

Radiological analysis. The penetration rate was similar in both groups. There was a good correlation between the radiological and direct measurements of UHMWPE wear (R² = 0.95), except that the radiological measurement under-

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**Table II. Results of the interferometry measurements on the non-weight-bearing and weight-bearing surfaces on all heads at x 40 magnification**

<table>
<thead>
<tr>
<th></th>
<th>Ra (mm)</th>
<th>Rpm (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alumina ceramic head</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-weight-bearing surface</td>
<td>7.69 (2.23 to 26.75)</td>
<td>9.05 (75.89 to 263.64)</td>
</tr>
<tr>
<td>Weight-bearing surface</td>
<td>40.12 (13.22 to 198.72)</td>
<td>98.21 (578.34 to 1329)</td>
</tr>
<tr>
<td><strong>Zirconia ceramic head</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-weight-bearing surface</td>
<td>6.78 (2.67 to 2789)</td>
<td>8.89 (69.98 to 271.34)</td>
</tr>
<tr>
<td>Weight-bearing surface</td>
<td>36.21 (12.78 to 199.21)</td>
<td>101.24 (607.34 to 1381)</td>
</tr>
</tbody>
</table>

* the values are given as the mean and range
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estimated the direct measurement by a mean of 0.09 mm (SD 0.012) in the alumina group and by a mean of 0.03 mm (SD 0.021) in the zirconia group. The mean linear penetration rate was 0.11 mm/yr (0.09 to 0.19) in the hips with alumina heads and 0.12 mm/yr (0.10 to 0.2) in the hips with zirconia heads. This difference was not significant (p = 0.195).

In the alumina head group, the mean linear penetration of the UHMWPE liner was 0.10 mm/yr (0.09 to 0.12) in hips with low Ra and Rpm values (13.22 nm and 85.91 nm, respectively). The mean linear penetration rate of the UHMWPE liner was 0.13 mm/yr (0.07 to 0.23) in hips with high Ra and Rpm values (198.72 nm and 1329 nm, respectively). This difference was significant (p = 0.041). In the zirconia head group, the mean linear penetration rate of the UHMWPE liner was 0.09 mm/yr (0.07 to 0.14) in hips with low Ra and Rpm values (12.78 nm and 92.99 nm, respectively). The mean linear penetration rate of the UHMWPE liner was 0.12 mm/yr (0.08 to 0.22) in hips with high Ra and Rpm values (199.21 nm and 1381 nm, respectively). This difference was significant (p = 0.039).
In the alumina head group, the mean UHMWPE liner linear penetration rate was 0.231 mm/yr (0.17 to 0.26) for acetabular components associated with third-body debris and 0.07 mm/yr (0.06 to 0.11) for components without third-body embedded debris. This difference was significant (p = 0.003). In the zirconia head group, the mean UHMWPE liner linear penetration rate was 0.234 mm/yr (0.18 to 0.25) for acetabular components associated with third-body debris and 0.08 mm/yr (0.07 to 0.12) for components without third-body debris. This difference was significant (p = 0.004).

No correlation was found in either group, with the numbers available between the penetration rate of the UHMWPE and the following attributes: patient age, gender, and activity level; duration of implantation; and type of head, femoral and acetabular component (p > 0.05).

No hip in either group had detectable acetabular or femoral osteolysis radiologically.

**Discussion**

Ceramics such as alumina and zirconia have been used for 40 years as materials for femoral heads in THR because of their mechanical properties, specifically high fracture toughness, surface hardness, and low coefficients of friction.\(^1\,^{12},^{15},^{16}\) It has become apparent from radiological studies that the mean penetration rate with a metal femoral head is invariably higher than with a ceramic femoral head. Overall, the penetration rate is a mean 2.7 times (1.7 to 4) higher with a metal-on-UHMWPE bearing than with ceramic-on-UHMWPE.\(^3\,^{4},^{17},^{18}\) However, some studies have produced conflicting results.\(^3\,^{4},^{10},^{19} - ^{23}\) The results of the current study demonstrated that the penetration rates were close to the level of the so-called osteolysis threshold (0.10 mm/year\(^12\,^{24}\)) irrespective of surface roughness (Ra and Rpm values) of the femoral head. No hip in either group showed any radiologically detectable acetabular or femoral osteolysis, partly because the ceramic-on-UHMWPE bearing has a low penetration rate, and partly because follow-up was short.

One recent retrieval study confirmed a greater than 20% monoclinic phase transformation with surface cratering and substantial roughening in a zirconia head retrieved after three years.\(^7\) However, in another study,\(^24\) a zirconia ceramic head which had survived for ten years showed minimal phase transformation, a high-quality bearing surface, very low residual surface stresses and no change in surface roughness. By contrast, the same study\(^24\) contained a zirconia head, retrieved at eight years, that appeared as badly transformed as that described by Haraguchi et al.\(^7\) Thus, for reasons which are currently unclear, some zirconia heads undergo phase transformation and some do not, even a decade after implantation. In the current retrieval study, monoclinic phase transformation was less than 20% in 23 zirconia ceramic heads and 25% in only one. Minimal phase transformation of the zirconia head appeared to result in a low penetration rate of the UHMWPE liner, similar to that of an alumina head. The difference of retrieval times (alumina head 11.3 years, zirconia head 9.8 years) may also be a factor.

Santos et al\(^1\) reported that there was no clear correlation between increasing monoclinic surface content and surface roughness. They suggested that other factors, such as third-body wear or contact with the acetabular shell during reduction manoeuvres, were likely to play a crucial role in the long-term health of the zirconia head surface. Kim, Ritchie and Hardaker\(^25\) and Kim\(^26\) observed that transfer of metal debris to a ceramic head occurs even with relatively minor scratching. Black discoloration of a ceramic head can occur simply by light scratching of the head on a metal surface and results in an increase in surface roughness and wear of the UHMWPE liner.\(^25\,^{26}\) The findings in our study confirmed that the mean wear rate of UHMWPE with third-body embedded debris was significantly higher in both groups (0.231 mm/yr and 0.234 mm/yr, respectively) than the mean wear rate of UHMWPE without embedded debris (0.07 mm/yr and 0.08 mm/yr, respectively). Consequently, at operation, care needs to be taken to avoid contact between the ceramic femoral head and any metallic materials. Because of the hardness of ceramic, one might expect more metal to be transferred to ceramic than to other materials used to make a prosthetic femoral head.\(^27\) Other sources of contamination should be controlled as far as possible.

Our study has some limitations. The surface characteristics and wear pattern of the retrieved femoral heads may not be representative of the surface characteristics and wear pattern of well-functioning THRs. Additionally, the number of retrieved ceramic femoral heads that we examined was small and may affect our conclusions.

The study also has several strengths. We had complete clinical data on all patients from whom the femoral heads were retrieved. The study was performed in a population of patients all of whom had similar components from the same manufacturer.

In summary, the explanted zirconia heads with minimal phase transformation had a similar surface roughness and penetration rate of the UHMWPE liner as in the explanted alumina heads. However, the zirconia head may undergo progressive monoclinic transformation with time, resulting in a corresponding increase in surface roughness and UHMWPE liner penetration. Additional retrieval and tribological studies are needed to confirm or refute these observations.

**Supplementary material**

Tables showing the results of phase analysis of zirconia heads, direct and radiological measurements of linear penetration of UHMWPE and the relationship between linear penetration of UHMWPE and other factors are available on our website at www.jbjs.org.uk

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No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.
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