Phase transformation of a zirconia ceramic head after total hip arthroplasty

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We report two cases of surface deterioration of a zirconia ceramic femoral head associated with phase transformation after total hip arthroplasty. One head was retrieved at revision due to recurrent dislocation after six years and the other because of failure of the locking mechanism of the polyethylene liner after three years. The monoclinic content of the zirconia ceramics rose from 1% to about 30% on the surface of the heads. SEM revealed numerous craters indicating extraction of the zirconia ceramics at the surface. Surface roughness increased from an initial value of 0.006 μm up to 0.12 μm. This is the first report to show that phase transformation of zirconia ceramics causes deterioration of the surface roughness of the head in vivo after total hip arthroplasty.

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The use of zirconia ceramics may reduce the rate of failure in total hip arthroplasty (THA) since they have a higher mechanical strength than alumina ceramics. The crystal structure, however, is unstable and low-temperature ageing can occur in vitro because of phase transformation. There is no description of phase transformation of zirconia ceramics after THA in the English literature. We report two cases of deterioration and increase in surface roughness of a zirconia ceramic femoral head associated with phase transformation after THA.

Patients and Methods

Between 1992 and 1994, in a clinical trial directed at obtaining Japanese regulatory approval for general usage, 18 patients had 21 cementless THAs using a Kobelco system (H-5; Kobe Steel Ltd, Kobe, Japan) with a modular zirconia femoral head. Sterilisation was by ethylene oxide gas and autoclaving was not used. Two patients (two hips) required a revision procedure and the retrieved heads were analysed.

The ceramic used was yttria tetragonal zirconium oxide polycrystal (Y-TZP) containing 3 mol% yttrium oxide for stabilisation. The commercial starting powder was produced by a coprecipitation method. The material was processed by cold isostatic pressing, followed by pressureless sintering. Hot isostatic pressing was then used to achieve a density of more than 99.9% with polishing of the surface as the final process. The chemical composition and the physical and mechanical properties of the Y-TZP are shown in Table I. The surface roughness (measured in Ra) of a new Y-TZP head was 0.006 μm of Ra (arithmetic mean of the absolute value of the measured profile height deviation as measured from the graphical centre line), and the monoclinic content, calculated by x-ray diffraction, was 1%. The Y-TZP meets the criteria of the International Organisation for Standardisation (ISO) 13356 and the American Society for Testing and Materials (ASTM) F1873 (Table I).

The surfaces were observed by the naked eye and light microscopy. The surface roughness was measured using a contact surface profilometer (ST-501; Mitutoyo Corporation, Kawasaki, Japan) at the pole of the femoral head, at the equator and 5 mm below the equator, and the Ra values were calculated. The surface and inner bulk structure were observed by SEM. The monoclinic content of the surface of the Y-TZP head was calculated by x-ray diffraction at the same sites.

Case 1. A 58-year-old woman with bilateral osteoarthritis of the hip had a right cementless THA in January 1994 and a similar operation on the left in February 1994 using the H-5 system. She had relief from pain and was able to walk without assistance. Five years later she developed recurrent dislocation of the left hip. Computer-aided radiological measurements showed polyethylene wear to be 1.6 mm (Fig. 1). Revision hip arthroplasty was undertaken using a femoral head of 46 mm diameter to improve stability.
Case 2. A 49-year-old man sustained a fracture-dislocation of the left hip in a traffic accident in 1988. He was treated by open reduction and internal fixation, but developed post-traumatic osteoarthritis and underwent cementless THA in March 1994 using the H-5 system (Figs 2A and 2B). Although there was relief from pain and he could walk without assistance, he developed discomfort and instability in January 1997 without any obvious cause. Radiographs showed dislodgement of the ring of the polyethylene liner (Fig. 2C). At revision both the acetabular cup and the femoral stem were found to be stable. The polyethylene liner and the femoral head were exchanged.
Results

The retrieved heads appeared glossy to the naked eye, but photomicrographs showed surface roughening (Fig. 3) which increased at the pole of the femoral head, at the equator, and 5 mm below the equator (Table II). It was lowest at the pole and highest 5 mm below the equator. SEM of the surface of the heads showed numerous craters delineated by the cracks indicating extraction of the surface layers of Y-TZP (Fig. 4), while SEM of the surface of an unused head revealed a smooth polished surface with some small voids of less than 0.5 μm (Fig. 5). SEM of the surface of the crater revealed a stratified crystal structure with some voids suggesting transformation from the tetragonal phase to the monoclinic phase (Fig. 6A) and SEM of the inner bulk of the heads showed a tetragonal crystal structure and no abnormality suggesting phase transformation (Fig. 6B). The monoclinic contents on the surface were about 30% in case 1 and 20% in case 2 (Table II). They were similar regardless of the site of measurement.

Discussion

Zirconia ceramics were introduced in 1985 as a promising new material for THA. The superior mechanical strength, in comparison with alumina ceramics, could reduce the rate of fracture of femoral heads while allowing the use of

Table II. Surface roughness in Ra and monoclinic content of retrieved zirconia heads

<table>
<thead>
<tr>
<th>Site of measurement</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ra (μm)</td>
<td>Monoclinic content (%)</td>
</tr>
<tr>
<td>Pole</td>
<td>0.02</td>
<td>36.6</td>
</tr>
<tr>
<td>Equator</td>
<td>0.03</td>
<td>28.0</td>
</tr>
<tr>
<td>Below the equator</td>
<td>0.12</td>
<td>35.4</td>
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</tbody>
</table>

Fig. 3
Case 1. Photomicrographs of the retrieved zirconia head. Diagram showing A) the pole of the head, B) at the equator of the head, C) 5 mm below the equator and D) the lower border of the head. The distribution of the craters varied with the site. The surface near the pole (A) was relatively smooth while that near the equator was rough (C). The arrows on the diagram indicate the sites of observation.

Fig. 4
Case 1. SEM of the retrieved zirconia head. The craters delineated by the cracks indicate extraction of the surface layers of the zirconia ceramics.
heads\textsuperscript{4} of smaller diameter and retaining the excellent wear performance against polyethylene.\textsuperscript{5,6} These characteristics were considered to be important for improving the longevity of a THA. However, recently published results of THA using a zirconia head have not been encouraging.\textsuperscript{7,8} One cause is thought to be phase transformation in vivo.\textsuperscript{9}

Zirconia ceramics have three phases of crystal structure, which transform according to temperature. The monoclinic phase transforms into a tetragonal phase at less than 1100°C, while the tetragonal phase transforms into the cubic phase at 2370°C. Since the tetragonal phase is unstable, but shows the greatest mechanical strength of the three phases, Y-TZP was used for the surgical grade zirconia ceramics. Transformation from the tetragonal phase into the monoclinic phase brings a 3\% increase in the volume of ceramics. While this phase transformation plays an important role in increasing the mechanical strength in Y-TZP, when it occurs extensively it may cause an increase in the surface roughness. Phase transformation in Y-TZP is induced at a relatively low temperature in the presence of water and pressure.\textsuperscript{1} Therefore, sterilisation of Y-TZP in an autoclave is contraindicated.
In case 1 the cause of the recurrent dislocation appeared to be wear of the polyethylene. The retrieved polyethylene liner showed a linear wear pattern superolaterally, but no abnormal abrasive wear of the rim suggesting impingement. SEM failed to show the scratches caused by dislocation on the surface of the retrieved head. The distribution of the craters on the surface of the Y-TZP head was circumferential around the axis of the neck and depended on the site on the head. These findings suggest that recurrent dislocation may not have been the cause of the surface roughening. In case 2, the head was retrieved because of dislodgement of the ring of the polyethylene liner. Laboratory tests carried out by the manufacturer have shown that impingement of the femoral neck on the polyethylene liner caused dislodgement of the ring and the locking mechanism has now been changed.

The cause of phase transformation of the Y-TZP heads is still speculative, but heat and pressure contribute. Lu and McKellop\textsuperscript{11} reported that the surface temperature of the polyethylene of a Y-TZP head rose to 99° in a hip simulator.

An interesting finding is that the monoclinic content is similar all over the surface of the head, while surface roughness varies. This implies that phase transformation may not always cause uniform surface roughening, and that the manufacturing process of Y-TZP may influence surface deterioration after phase transformation. SEM of an unused Y-TZP head has shown small voids on the surface, but they are so small that they do not affect the Ra value. Stress concentration on the voids may cause acceleration of phase transformation of the head. Further analysis regarding phase transformation of other Y-TZP heads with a different manufacturing process is required, and careful follow-up is essential after THA using this head.

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.

References


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