Roughness and Surface Polarity of Retrieved Zirconia Femoral Heads

Introduction: Recent clinical studies found no reduction in UHMWPE wear using yttria-stabilized zirconia (Y-TZP) instead of cobalt chromium alloy (CoCr) femoral heads [1-5]. The purpose of this study was to compare the roughness and surface polarity of retrieved Y-TZP and magnesia-stabilized zirconia (Mg-PSZ) femoral heads and evaluate the influence of time in vivo. The roughening of Y-TZP due to phase transformation in vivo is well-documented [6-10], while Mg-PSZ does not roughen or undergo phase transformation in vivo [6]. However, the influence of phase transformation on the nature of the roughness (surface polarity or skewness, Ssk) of retrieved ZrO₂ heads has not been reported. We hypothesized that phase transformation associated with the increased roughness of Y-TZP would increase skewness and thus the wear potential.

We hypothesized that phase transformation associated with the increased roughness of Y-TZP would increase skewness and thus the wear potential of the heads, and that no such increase would occur with Mg-PSZ heads.

Materials and Methods: Y-TZP (n = 44) and Mg-PSZ (n = 50) femoral heads, including seven Y-TZP and 12 Mg-PSZ heads from a previous study [6], were retrieved from revision THA (Table 1). The retrievals were cleaned and scanned along with five never-implanted heads of each type by optical profilometry (magnification = 10x, scan size 633 µm x 476 µm) at three locations per specimen. After subtracting the curvature of the heads, roughness statistics (Sa, Sq, Sp, Ssk, Sku) were calculated and averaged together for each specimen. The surface polarity ratio 3*Ssk/Sku, which is less sensitive to noise than skewness Ssk alone [11], was also calculated. Roughness parameters and polarity were then correlated to age in vivo, with p < 0.05 for significance.

Table 1. Summary of the retrieved ZrO₂ heads evaluated in this study.

<table>
<thead>
<tr>
<th>ZrO₂ Type</th>
<th>Manufacturer</th>
<th>n</th>
<th>Age in vivo (years)</th>
<th>Avg. ± S.D.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-TZP</td>
<td>CeramTec</td>
<td>15</td>
<td>4.65 ± 3.9</td>
<td>0.04-10.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Morgan</td>
<td>26</td>
<td>11.4 ± 4.3</td>
<td>0.04-17.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Saint Gobain</td>
<td>3</td>
<td>7.19 ± 2.4</td>
<td>4.50-8.93</td>
<td></td>
</tr>
<tr>
<td>Mg-PSZ</td>
<td>Xylon</td>
<td>50</td>
<td>5.80 ± 4.5</td>
<td>0.01-13.3</td>
<td></td>
</tr>
</tbody>
</table>

Results: The roughness Sa and Sq of Y-TZP heads increased exponentially with age in vivo (p < 0.001, r² > 0.60), while the roughness of Mg-PSZ heads decreased with age (p > 0.099; Figure 1). Polarity data revealed the roughness of Y-TZP heads to be caused by positive features, irrespective of manufacturer (and age in vivo, p > 0.72), with the roughness of Mg-PSZ heads attributable to negative features and decreasing with age in vivo (p = 0.13 for Ssk, p = 0.008 for polarity ratio; Figure 2). Comparing only long-term retrievals (5+ years in vivo), the roughness data of all retrievals were greater than that of never-implanted specimens, with Morgan and Saint Gobain Y-TZP heads exhibiting considerable roughening but CeramTec Y-TZP and Xylon Mg-PSZ heads exhibiting only slight roughening (Table 2). The polarity ratio of long-term retrievals was lower even among Y-TZP retrievals.

Discussion: The increased roughness of long-term Y-TZP retrievals was expected [6-10], but the relative smoothness of those made by CeramTec (indicated by ▲ in Figure 1) was surprising given that artificially aged CeramTec Y-TZP heads have been shown to exhibit increased roughness due to phase transformation [12]. The relatively stable topography of Mg-PSZ heads previously reported up to 8.9 years in vivo [6] was observed up to 13.3 years in the current study.

Positive features such as raised edges have been reported to adversely affect wear rates in the lab [13,14]. The strongly positive surface polarity of Morgan and Saint Gobain Y-TZP retrievals combined with the increased average roughness suggest an accelerated wear potential with age in vivo, but the positive surface polarity and low roughness of CeramTec Y-TZP retrievals does not. In contrast, the surface polarity of Mg-PSZ retrievals was negative, with a significant inverse correlation to age in vivo. A surface described by negative features would tend to entrap lubricant for better wear characteristics [15]. Recent hip simulator tests found Mg-PSZ femoral heads to exhibit significantly lower cross-linked UHMWPE liner wear compared to CoCr femoral heads [16]. Combined with the low average roughness and negative polarity observed in retrieved Mg-PSZ femoral heads, these data suggest superior wear characteristics when articulating against cross-linked UHMWPE in vivo.

Mg-PSZ zirconia ceramics remained stable and did not roughen or develop raised edges after 13.3 years in vivo, in contrast to Y-TZP ceramic femoral heads manufactured by Morgan or Saint Gobain. Y-TZP heads manufactured by CeramTec were surprisingly smooth up to 10.4 years in vivo, but like the Morgan Y-TZP retrievals exhibited a strongly positive surface polarity that did not appear to increase with age in vivo. The low roughness and increasingly negative surface polarity observed on Mg-PSZ retrievals suggest a lower wear potential in vivo.

Table 2. Summary of the retrieved ZrO₂ head retrieved in vivo.

<table>
<thead>
<tr>
<th>ZrO₂ Type</th>
<th>Manufacturer</th>
<th>n</th>
<th>Roughness Parameters (nm)</th>
<th>Surface Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sa Sq Sp Ssk Ratio</td>
<td>Sa Sq Sp Ssk Ratio</td>
</tr>
<tr>
<td>A. Long-term retrievals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y-TZP</td>
<td>CeramTec</td>
<td>8</td>
<td>6.56 8.29 52.5 0.361</td>
<td>0.296</td>
</tr>
<tr>
<td></td>
<td>Morgan</td>
<td>24</td>
<td>28.0 36.5 282 0.555</td>
<td>0.301</td>
</tr>
<tr>
<td></td>
<td>Saint Gobain</td>
<td>2</td>
<td>27.1 35.0 245 -0.044</td>
<td>0.106</td>
</tr>
<tr>
<td>Mg-PSZ</td>
<td>Xylon</td>
<td>28</td>
<td>8.91 10.7 79.4 -0.160</td>
<td>0.160</td>
</tr>
<tr>
<td>B. Never-implanted heads</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y-TZP</td>
<td>CeramTec</td>
<td>5</td>
<td>4.69 5.92 44.1 0.477</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>Xylon</td>
<td>5</td>
<td>8.49 10.7 79.4 -0.222</td>
<td>0.077</td>
</tr>
</tbody>
</table>

Roughness and Surface Polarity of Retrieved Zirconia Femoral Heads

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INTRODUCTION

• Recent clinical studies found no reduction in UHMWPE wear using yttria-stabilized zirconia (Y-TZP) instead of cobalt chromium alloy (CoCr) femoral heads
• The purpose of this study was to compare the roughness and surface polarity of retrieved Y-TZP and magnesia-stabilized zirconia (Mg-PSZ, ASTM F2393) femoral heads and evaluate the influence of time in vivo
• We hypothesized that phase transformation associated with the increased roughness of Y-TZP would increase skewness and thus the wear potential of the heads, and that no such increase would occur with more stable Mg-PSZ heads

MATERIALS AND METHODS

• Y-TZP (n = 45) and Mg-PSZ (n = 51) femoral heads were retrieved from revision THA:

<table>
<thead>
<tr>
<th>ZrO₂ Type</th>
<th>Manufacturer</th>
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<th>Age in vivo (years)</th>
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<th>Range</th>
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<td>3</td>
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<td>4.5-8.93</td>
<td></td>
</tr>
<tr>
<td>Mg-PSZ</td>
<td>Xylon</td>
<td>51</td>
<td>5.95 ± 4.6</td>
<td>0.01-13.4</td>
<td></td>
</tr>
</tbody>
</table>

• The retrievals were cleaned and scanned along with five never-implanted heads of each type by optical profilometry (magnification = 10x, scan size 633 µm x 476 µm) at three locations per specimen
• After subtracting the curvature of the heads, roughness statistics (Sa, Sq, Sp, Ssk, Sku) were calculated and averaged together for each specimen
• The surface polarity ratio 3*Ssk/Sku, which is less sensitive to noise than skewness Ssk alone, was also calculated
• Roughness parameters and polarity were then correlated to age in vivo, with p < 0.05 for significance

RESULTS

Table 1. Summary of the retrieved ZrO₂ heads evaluated in this study.

Figure 1. Roughness data (Sa) vs. age in vivo for Y-TZP (△, dotted regression curve) and Mg-PSZ retrievals (□, solid regression line). CeramTec Y-TZP retrievals are indicated by solid triangles (▲).

• The roughness Sa of all Y-TZP heads increased exponentially with age in vivo (p < 0.001)
• However, the roughness of Y-TZP heads made by CeramTec was best described by linear regression (p = 0.01)
• The roughness of Mg-PSZ heads decreased with age (p = 0.06)

Table 2. Roughness and polarity data from A. long-term ZrO₂ retrievals (5+ years in vivo) and B. never-implanted ZrO₂ heads.

Figure 2. Polarity ratio data vs. age in vivo for Y-TZP (△, dotted regression line) and Mg-PSZ retrievals (□, solid regression line). CeramTec Y-TZP retrievals are indicated by solid triangles (▲).

• Polarity data revealed the roughness of Y-TZP heads to be mainly caused by positive features, irrespective of manufacturer (and age in vivo, p > 0.90)
• The roughness of Mg-PSZ heads was attributable to negative features and decreased with age in vivo (p = 0.004)

• The polarity ratio of long-term retrievals was lower even among Y-TZP retrievals, in part due to grain pullout in Morgan heads

Figure 3. Optical profilometry scans of the pole region of four retrieved ZrO₂ heads: A. CeramTec Y-TZP, 8.2 years in vivo; B. Morgan Y-TZP, 9.3 years; C. Saint Gobain Y-TZP, 8.9 years; D. Xylon Mg-PSZ, 9.4 years. Phase transformation is readily evident in the topography of the Morgan and Saint Gobain heads, but not the CeramTec or Xylon heads.

DISCUSSION

Table 2. Roughness and polarity data from A. long-term ZrO₂ retrievals (5+ years in vivo) and B. never-implanted ZrO₂ heads.

• Long-term Y-TZP retrievals made by Morgan and Saint Gobain exhibited increased roughness as expected, but the relative smoothness of those made by CeramTec was surprising
• The relatively stable topography of Mg-PSZ heads previously reported up to 8.9 years in vivo was observed up to 13.4 years in the current study
• Positive features such as raised edges have been reported to adversely affect wear rates in the lab
  - The strongly positive surface polarity of Morgan and Saint Gobain Y-TZP retrievals combined with the increased average roughness suggest an accelerated wear potential with age in vivo
  - However, the low average roughness of long-term CeramTec Y-TZP retrievals underscores that not all Y-TZP is created equal
• In contrast, the surface polarity of Mg-PSZ retrievals was negative, with a significant inverse correlation to age in vivo
  - A surface described by negative features would tend to entrap lubricant for better wear characteristics
  - Recent hip simulator tests found Mg-PSZ femoral heads to exhibit significantly lower cross-linked UHMWPE liner wear compared to CoCr heads
• Retrieval data suggest Mg-PSZ heads will exhibit superior wear characteristics in vivo

CONCLUSIONS

Table 2. Roughness and polarity data from A. long-term ZrO₂ retrievals (5+ years in vivo) and B. never-implanted ZrO₂ heads.

• Retrieved Mg-PSZ zirconia femoral heads remained stable and did not roughen or develop raised edges after 13.4 years in vivo
• In contrast, Morgan Y-TZP heads exhibited considerable roughening and a strongly positive surface polarity despite grain pullout observed in older retrievals
• CeramTec Y-TZP heads were surprisingly smooth up to 10.4 years in vivo
• The low roughness and increasingly negative surface polarity observed on Mg-PSZ retrievals suggest a lower wear potential in vivo

57th Annual Meeting of the Orthopaedic Research Society, January 13-16, 2011, Long Beach, California