Qualitative analysis of polyethylene wear in a bipolar femoral prosthesis: A case report

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ABSTRACT

We researched the qualitative changes in the polyethylene of a bipolar head retrieved at revision occurring in vivo using optical microscopy and Fourier transform infrared spectroscopy. The bearing surface of the outer head was smooth with no definable scratches delamination. However, the evidence of delamination of the beveled throat region and cracking at the base of the leaf was noticed. The degree of oxidation was different in each area of the polyethylene in the bearing component and that of the rim was shown to be higher than that of the bearing surface. Comparing the rate of ketone and ester, ketone binding was frequently found around the prosthetic rim rather that at the bearing surface. However, the ratio of ester at the surface was higher than that at the deep area of the same rim. We considered these results showed local environmental effects in vivo play a significant role in dictating the response.

Key words: bipolar hip arthroplasty, polyethylene, wear debris, oxidation, Fourier transform infrared spectroscopy

INTRODUCTION

Wear and the generation of ultra high molecular weight polyethylene (UHMWPE) wear particles is now considered the most important cause of long term failure in total hip arthroplasty. Wear debris originating from the contact of the bipolar head with the femoral neck in 1994, and subsequently other reports have described acetabular osteolysis following bipolar hip arthroplasty. Polyethylene wear and subsequent osteolysis have also been recognized as severe problems in bipolar hip arthroplasty.

The purpose of this paper is to investigate qualitative changes in polyethylene in vivo using an
outer head that was retrieved at revision. We reported a case of a female patient in whom the polyethylene component failed following bipolar hip arthroplasty with acetabular reaming. This patient had marked acetabular osteolysis; however, neither osteolysis nor any radiolucent lines were apparent around the femoral stem.

MATERIALS AND METHODS

This case involved a female patient who was 49 years old at the time of the primary operation. She had suffered from dysplastic hip osteoarthritis which was treated with primary arthroplasty with the reaming of the acetabulum and implantation of a bipolar hip arthroplasty with an Aufranc-Turner cemented stem with a 22.225 mm inner femoral head. When this patient returned to the clinic with hip pain 15 years after the primary operation, osteolysis around the outer head was recognized. When the patient was 64 years old, revision was performed and the outer head was retrieved. Therefore, we have been able to follow this patient for fifteen years following the primary operation.

In order to research the qualitative changes in the polyethylene occurring in vivo, we investigated the shape, location and volume of the polyethylene wear in the retrieved outer head. The wear analysis was performed on this component to determine wear rate penetration in millimeters per year. This calculation was made utilizing mathematical calculations of polyethylene thickness. The size of it was identified, manufacturing blueprints were matched up to determine the original polyethylene thickness at the pole region, and the outer head was measured in the same region to define the thickness difference. This difference between the original and actual thickness was used in conjunction with the implantation age of the component to calculate the wear rate. Also, optical microscopy and Fourier transform infrared (FT-IR) spectroscopy was used to assess the oxidation of the polyethylene. Thin sections approximately 0.025 mm thick were cut with a microtome, parallel to the radial direction, through the leaflets and bearing surface. The sections were placed on a microscope slide with a cover slip glued over the section in order to keep them flat. The sections were then examined with transmitted plane and polarized light microscopy. The same 0.025 mm sections used for the optical microscopy were used to measure the IR spectra by transmission, placing the sections on a KBr plate on a Nicolet-Plan FT-IR microscope. The degree of oxidation was measured as the ratio C=O:PE, where C=O represents the area under the IR spectrum between 1749–1691 cm\(^{-1}\) and PE is the C-C rocking band 739–708 cm\(^{-1}\) (Graph 1).

RESULTS

The roentgenograms showed that the outer head had moved medially, appearing similar to the protrusio acetabli of rheumatoid arthritis. The extent of the clear zone around the outer head widened gradually from 12 years after the primary operation and finally reached a maximum of 5 mm. However, as there was no osteolysis or any clear zone around the stem, we only replaced the bipolar outer head with allo-bone grafting of the acetabular defect (Fig.1).

Figure 1 Case. The patient was female and her age at revision was 64 years, followed up for 15 years. The clear zone around the outer head on the roentgenograms widened gradually twelve years later postoperatively and the outer head moved to the supero-medial direction, so she felt hip pain at the same time.
The outer head diameter was 44 mm. The bearing surface of the outer head was smooth, polished and glistening with no definable scratches or delamination (Fig. 2). The average diameter of the bearing socket was 22.771 mm (normal diameter 22.377 mm). Average diameter of the ‘throat’ was 20.015 mm (normal value 19.380 mm). The wear on the bearing surface was 0.197 mm. This represented an annual linear wear rate of 0.0131 mm.

Features such as a black band could not be seen in the main socket load-bearing region with an optical microscopy using reflected light (Fig. 4). With transmitted light, this black band was visible approximately 0.70 mm below the surface in many regions of the polyethylene component, but not uniformly over the section. This is equivalent to the white band seen under reflected light microscopy (Fig. 5). These optical effects were caused by micro fractures produced in the brittle, highly crystalline regions. Some leaflets exhibited variable degrees of recrystallization as determined by a black subsurface band, with relatively little on the inner surface but severe in the area of the delamination on the beveled surface. In the beveled region under polarized light, the development of the recrystallization within the resin grains was clearly apparent.

Visible discoloration of the beveled polyethylene rim was apparent in places. Evidence of delamination of the beveled throat region and cracking at the base of the leaf was noticed. Very little abrasive wear occurred on the beveled surface of the leaflet (Fig. 3).
Table 1 presents the FT-IR spectroscopy data. The degree of oxidation was different in each area of the polyethylene-bearing component. The degree of oxidation of the rim was shown to be higher than that of the bearing surface (Fig. 6) (Table 1). Comparing the ratio of ketone and ester, the ketone binding was frequently found around the prosthetic rim rather than at the bearing surface. However, the ratio of ester at the surface was higher than that at the deep area of the same rim. The distribution of the radiation-induced oxidation is of interest. In this case almost no oxidation was detectable in the lower region of the insert. All of the regions, which appeared clear, exhibit an oxidation ratio of between 0.18 and 0.28. The main crystallization changes occurred at the resin boundaries, as illustrated by the darkened boundaries. The area below the clear surface layer, i.e. rom 0.70 to 1.40 mm, had a maximum oxidation ratio of 0.33–0.41 and is where the delamination may occur.

**Figure 6** The number shows the area of the polyethylene insert.

### DISCUSSION

The mean annual wear rate with the 22 mm inner head in total hip arthroplasty (THA) was reported by Charnley and Halley in 1975 to be 0.09 mm, while Wrobleski found this to be 0.096 mm in 1993. In 1998, Ingemar et al. studied wear and migration rates in a series of 102 hip replacements randomised to have either a cemented polyethylene Charnley socket or a porous uncemented Harris-Galante type–1 cup using radiostereometric analysis. The mean annual wear rate was found to be 0.09 mm in the Charnley sockets and 0.1 mm in the Harris-Galante socket. Chun-Hsiung measured linear polyethylene wear in uncemented Osteonics components using digital and special software of their own design in 1998. The mean annual wear was 0.15 mm, which increased to 0.23 mm in hips showing evidence of osteolysis.

For bipolar prosthesis, Bose et al. reported a case that had osteolysis of the acetabulum and in which the mean annual wear rate of the retrieved outer head was 0.17 mm. Using radiographs showing the inner articulation of the bipolar hip prosthesis, Kusada and Kuroki also reported an 0.17 mm wear rate, and that there was no difference between the annual wear rate of hips with and without osteolysis. In this case, the mean annual wear rate of the bearing socket was 0.0131 mm. We think the wear results here are quite low. However, this result cannot be compared directly with other reports which used roentgenograms to assess liner wear rates and the mechanical-stress was not usually of uneven distributions in bipolar hip arthroplasty unlike THA. We found smooth surfaces within the socket region of this outer head which differed from the roughness often found in the acetabular cups of THA. We think that one reason is the reduction of friction with the dual bearing design. Another reason is the relative absence of third body

<table>
<thead>
<tr>
<th>Area</th>
<th>C=O</th>
<th>PE</th>
<th>C=O/PE</th>
<th>Ketone/Ester</th>
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<td>0.288</td>
<td>11.148</td>
<td>0.03</td>
<td>ND</td>
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<td>13.337</td>
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<td>4.187</td>
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</tbody>
</table>
wear of the bearing surfaces due to the locking system between the inner head and the bearing insert, as well as the narrow entrance in a bipolar hip prosthesis. Additionally, the insert wear in the socket region occurred in a surface region where there was minimum oxidation and no excessive recrystallization, where 0.70 mm of clear region remained. So the amount of wear was minor and the bearing surface looked polished, so no direct relationship was found between the wear in the inner articulation and occurrence of osteolysis in this study.

In bipolar hip prosthesis, not only the bearing surface, but also the polyethylene rim may produce wear debris. Some investigators have reported that a large amount of debris was due to severe rim abrasion by neck-cup contact and that this seemed to cause osteolysis. In addition, we found discoloration and extensive delamination occurred in the beveled region on some leaflets. The excessive crystallization that occurred approximately 0.70 mm below the insert surface, we think, was responsible for the delamination on some of the leaflets with the infusion of fluid and resultant discoloration. This was the result of recrystallization in the resin, which was able to take place by the increased chain mobility resulting from the radiation-induced oxidation.

The degree of oxidation was different within each area in a polyethylene insert, and that of the rim, which had been in contact with joint fluid, was shown to be higher than that of bearing surfaces. It was our understanding that the degree of oxidation at the point of femoral neck contact was higher than the other areas around the rim.

It is possible that supersonic waves are generated in the joint fluid with the regular fluctuations of pressure that occur with load bearing and movement. With this in mind, cavitation, where many small bubbles break out in the fluid during the decreasing the pressure phase would be generated. These bubbles expand with decreasing pressure and when their diameter reaches more than about 0.1 mm, they are crushed on the next increasing pressure phase. This phenomenon is called ‘cavitation collapse’ and the heat (about a few thousands degree Centigrade) increases locally at that time. The effect of heat makes a situation where oxidation occurs more easily at the same place in order to generate OH-free radicals from the hydro-molecular fluid. Additionally, the adjoining fluid moves rapidly due to the squeezing of fluid as neck-cup impingement continues, so the vibration which occurs encourages crysyallization in polyethylene. These factors — oxidation, crystallization and mechanical stress — may lead to polyethylene debris production.

In view of the distribution of ketone and ester, ketone binding was frequently found in the rim compared with the bearing surface. However, the ester rate was high at the surface of the rim that had contact with the joint fluid. This means that the polyethylene rim is also in an unstable situation, which easily oxidizes at the molecular level. The ester bindings usually exist at the end of a polyethylene chain after oxidation, so there should be many short chains at the surface of the rim; the cause is recrystallization due to vibration of the surface. This situation weakens the polyethylene and can cause occurrence of polyethylene debris.

CONCLUSION

Considering that the radiation during sterilization was uniform over such a small object as a bipolar implant, the variation in the degree of radiation induced recrystallization that varies with location indicates local environmental effects play a significant role in dictating the response. In bipolar prosthesis of the hip, the majority of polyethylene wear debris is generated from the rim and not the bearing surface. We believe the cause of polyethylene wear debris generated from the rim is closely related to oxidation and recrystallization of the material, which may be caused by cavitation, vibration and the creation of many short polyethylene chain segments due to joint fluid effects as well as neck-cup impingement.

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REFERENCES