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Highly Crosslinked Polyethylene Improves Wear But Not Surface Damage in Retrieved Acetabular Liners

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Abstract

Background Highly crosslinked polyethylene (XLPE) is believed to demonstrate better wear resistance than conventional polyethylene (CPE) in total hip arthroplasty.

Questions/purposes The purpose of this study was to compare visual damage scores and micro-CT measurements of penetration, a surrogate for wear, between matched retrieved XLPE and CPE acetabular liners.

Methods Thirteen XLPE acetabular liners were matched in terms of implant design (all were of the same design), patient age, sex, liner dimensions, duration of implantation, and reason for revision to a group of CPE liners that were retrieved in the same time period. Penetration resulting from the combination of wear and creep in the two groups of liners was measured with micro-CT. Surface damage was scored by two blinded observers using a surface damage system that considers the seven common damage modes: pitting, scratching, burnishing, abrasions, impingement, embedded debris, and delamination, and wear patterns were documented.

Results There was no difference ($p = 0.32$) in total damage score between the XLPE group (14 ± 4) and the CPE group (15 ± 5). However, there was three times greater penetration (odds ratio, 3.1; confidence interval, 2.3–5.1; $p < 0.001$) in the CPE group (0.18 ± 0.09 mm/year) than in the XLPE group (0.05 ± 0.07 mm/year). There was less volumetric loss in XLPE ($82 \pm$ SD 134 mm^3) versus the CPE group ($350 \pm$ SD 342 mm^3; $p = 0.017$).

Conclusions XLPE liners undergo less penetration as a result of creep and wear than CPE liners based on quantitative measurements provided by micro-CT, which was not apparent using damage scoring alone. This demonstrates the use of three-dimensional imaging techniques such as micro-CT for quantifying wear in retrieval studies.

Clinical Relevance In this study, XLPE had less wear but similar damage scores than CPE, allaying concerns that the beneficial wear properties of XLPE might come with a tradeoff arising from the increased brittleness of that material.

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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Introduction

THA is a highly successful procedure, but its survivorship has been limited by aseptic loosening and osteolysis [8, 16]. This process is closely related to the polyethylene debris generated at metal-on-polyethylene articulations [10, 22]. Highly crosslinked polyethylene (XLPE) has been an important development, demonstrating superior wear

Table 1. Patient demographics

Variable	XLPE	CPE	p value
Total number of patients	13	13	
Percentage of females (number)	62% (8)	62% (8)	1.00
Percentage of right side (number)	62% (8)	62% (8)	1.00
Age (years)*	61 ± 14	66 ± 13	0.46
Length of implantation (years)*	5 ± 3	5 ± 4	0.73
Body mass index (kg/m^2)*	32 ± 7	32 ± 9	0.98
Reason for revision	38% (5) instability;	31% (4) aseptic loosening;	0.18
	31% (4) infection;	23% (3) infection;	
	15% (2) aseptic loosening;	23% (3) instability;	
	8% (1) periprosthetic fracture;	15% (2) polyethylene wear and osteolysis;	
	8% (1) polyethylene wear and osteolysis	8% (1) periprosthetic fracture	
Revision history	77% (10) primary;	84% (11) primary;	0.51
	15% (2) first revision;	8% (1) first revision;	
	8% (1) second or third revision	8% (1) second or third revision	

* The data are given as mean ± SD; all others listed as the percentage of patients with the number in parentheses; XLPE = highly crosslinked polyethylene; CPE = conventional polyethylene.

properties to conventional polyethylene (CPE) in hip simulators [12] and clinical trials using radiographic evaluations [9, 18, 20, 23–25, 33]. It has been postulated that the reduction in wear debris will limit osteolysis and increase the longevity of total hip implants [7, 21, 26].

Despite this evidence for the superiority of XLPE, there have been concerns that crosslinking can increase material brittleness, leading to higher risks of rim fracture and damage. Recent retrieval studies have demonstrated no difference in damage and rim fractures between XLPE and CPE acetabular liners retrieved from patients [27, 30]. However, it is possible that the semiquantitative grading of damage resulting from wear may not correlate with the actual wear or the wear rate of the retrieved polyethylene liners. Micro-CT has been reported as a useful tool for quantifying wear in retrieval studies, including those of acetabular liners [28, 32].

The overall objective of this study was to compare wear and damage between matched retrieved XLPE and CPE acetabular liners. The specific purposes of this study were (1) to compare the visual damage scores and distribution of surface damage in these liners; and (2) to quantify depth of penetration of the liners using micro-CT as a proxy for wear.

Materials and Methods

Thirteen XLPE acetabular liners were retrieved under an institution review board-approved protocol between 1999 and 2011. These represented all the FDA-approved highly crosslinked liners of a specific design (Reflection XLPE; Smith & Nephew, Memphis, TN, USA) in the retrieval laboratory with a 26- or 28-mm head and implanted for at least 1 year. These retrieved liners were matched to a group of CPE liners of identical design (Reflection; Smith & Nephew) that were retrieved in the same time period. Fifty-four CPE liners were available for matching. These two groups were matched in terms of patient age, sex, liner dimensions, duration of implantation, and reason for revision (Table 1). If there were two or more matches, the liner belonging to the patient with the most identical body mass index measurement was chosen. Most of the liners were neutral liners with two 20° lipped liners in each group. The XLPE and CPE implants share a common design, polyethylene resin (GUR 105), and sterilization (ethylene oxide), with the only difference being the crosslinking of the polyethylene (10 Mrad gamma irradiation with remelting in the XLPE group). All operations were performed though a modified Hardinge approach. An uncemented proximal0coated stem (Synergy; Smith & Nephew) was used in each case. A cobalt-chrome femoral head was used in most cases with just one oxidized zirconium head used in each group.

Routine postoperative radiographs were obtained in the clinic. The abduction angle was determined from these digitized standard AP pelvic radiographs. The inclination of the acetabular cup was measured as the angle between the inter-teardrop line and the line bisecting the superior and inferior rims of the cup. This was done to ensure that any difference in damage and wear was not the result of cup malposition.

The groups appeared well matched, confirming the efficacy of our matching protocol. There was no difference

in the demographic data of the patients in both groups (Table 1). The mean age of the patients in the study was 63 ± SD 14 years old. The overall mean duration of implantation of the retrieved acetabular liners was 5 ± SD 4 years. Instability, infection, and aseptic loosening were the primary reasons for revision in both groups. There was also no difference in inclination angle between groups. The median abduction angle of the acetabular cups was 46° (range, 38°–52°) in the CPE group and 44° (range, 37°–51°) in the XLPE group.

The polyethylene liners underwent an identical sanitation protocol at our implant retrieval laboratory that included storage in 10% formalin solution and cleansing in 10% bleach solution. The articular surface and the rim were divided into eight areas, and the backside compartment was also inspected. These areas were evaluated with a validated surface damage scoring system [4], and the seven common damage modes were identified and scored. These included pitting, scratching, burnishing, abrasions, impingement, embedded debris, and delamination. Two blinded observers (H-NP, MGT) scored the damage according to the percentage of area affected and the severity of each damage mode.

Each liner was scanned using micro-CT and analyzed using a previously described approach [30, 32]. The surface geometry of each liner was reconstructed using a laboratory micro-CT scanner (eXplore Vision 120; GE Healthcare, London, Ontario, Canada). Scans were completed using an isotropic resolution of 50 µm. Three-dimensional micro-CT analysis software (MicroView Version 2.2; GE Healthcare) was used to generate three-dimensional surfaces from the scans. The retrieved liner geometries were coregistered to never-implanted scanned geometries of the same size, and the deviations between the two (resulting from wear and creep) were quantified. The maximum depth of penetration was measured for each retrieved liner, and the wear rate was calculated by dividing the penetration by the time in situ. The volumetric loss as quantified by micro-CT was also calculated (Figs. 1, 2).

Statistical analysis was performed with SPSS statistical software (Version 11.0; SPSS, Chicago, IL, USA). Univariate analysis was performed with chi square or the Fisher's exact test for comparison of proportions between two categorical data. The Mann-Whitney U test was used to compare the nonparametric data between two independent samples. A p value < 0.05 was considered significant.

Results

There was no difference between groups (p = 0.32) for total damage score (Table 2) or for the bearing, rim, or backside surfaces damage scores. The most common damage modes

Fig. 1 An example is shown of the reconstructed three-dimensional geometry acquired using micro-CT for a CPE liner with severe bedding-in deformation.

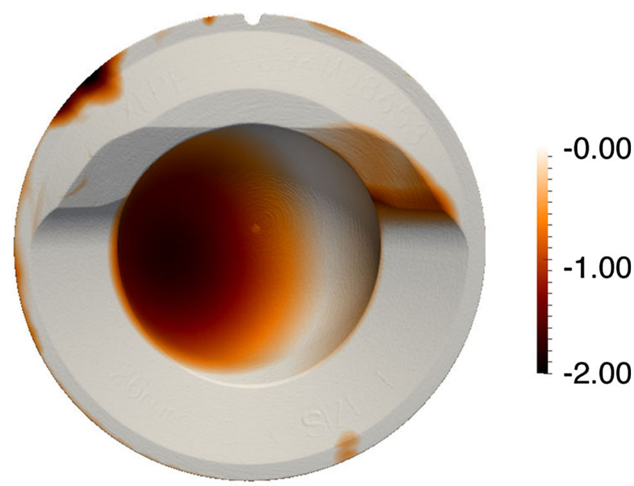

Fig. 2 Example deviation map is shown from micro-CT imaging revealing deviations (resulting from wear and creep) in a XLPE liner. Scale is in millimeters.

in the XLPE group were abrasion, scratching, and cold flow. The most common damage modes in CPE were burnishing, abrasion, and cold flow. The mean abrasion damage score was higher (p = 0.03) in the XLPE group (9 ± SD 5) than the CPE group (3 ± SD 2), whereas the mean burnishing score was higher (p = 0.02) in the CPE group (8 ± SD 5) than the XLPE group (3 ± SD 2). The superior quadrants demonstrated greater mean damage scores (19 ± SD 9) than the inferior quadrants (16 ± SD 8) in both groups. No rim fractures were detected in either group.

There was three times greater penetration (odds ratio, 3.1; confidence interval, 2.3–5.1; $p < 0.001$) in the CPE group (mean 0.18 ± SD 0.09 mm/year) versus the XLPE

group (mean 0.05 ± SD 0.07 mm/year) (Table 3). In the CPE group, maximum penetration ranged from 0.09 mm to 5 mm, whereas in the XLPE group, maximum penetration ranged from 0 mm to 2 mm. The amount of head penetration was less for the XLPE in all areas: the articular surface (mean 0.3 mm ± SD 0.5 mm, p = 0.042), rim (0.14 ± SD 0.18 mm, p = 0.009), and backside of the liner (0.08 ± SD 0.13 mm, p = 0.042). There was less volumetric loss in XLPE (82 ± SD 134 mm^3) versus the CPE group (350 ± SD 342 mm^3; p = 0.017). There was no correlation between the amount of articular surface damage and depth of penetration (r^2 = 0.075, p = 0.22).

Discussion

Highly crosslinked polyethylene has been developed with superior wear properties to conventional polyethylene [12, 17, 25, 33]. It has been postulated that the reduction in wear debris will limit osteolysis and increase the longevity of the implants [26, 27, 30]. However, it is possible that the semiquantitative grading of damage resulting from wear may not correlate with actual wear or the wear rate of the retrieved liners. This fact is confirmed by our study, which demonstrated that although there was no major difference in surface damage scores between polyethylene types, there was a substantial decrease in head penetration (a surrogate for wear) with the use of XLPE.

Like with all retrieval studies, our study is limited by its retrospective nature and by examining failed implants, which may not be representative of well-functioning implants. The micro-CT measurements of penetration included the initial creep-dominated phase as well as the subsequent slower phase of polyethylene wear. In vitro studies have demonstrated that creep continues for 2 million loading cycles [11, 14], which may be achieved in 3 months to 2 years postsurgery [15]. The actual steady-state wear rate for these liners may be considerably less than the penetration rate presented here. However, this limitation affects both groups equally [14], and therefore the relative steady-state wear rates between them would be maintained or may even be proportionately more disparate. Finally, we relied on never-implanted reference components for the prewear geometry of the liners, which may vary from the true prewear state of each component as a result of manufacturing tolerances. Once again, this limitation affects both groups equally, and the tolerances are much lower than the amount of wear seen, especially in the CPE group. The relative level of penetration between the XLPE and CPE groups would thus be maintained.

Previous retrieval studies described the general condition and apparent wear of XLPE through damage scoring [4–6, 19, 29]. However, these studies did not include quantitative wear measures nor did they measure performance between XLPE and an identical (with the exception of crosslinking) contemporary CPE component. Schroder et al. [30] reported no difference in visual damage between retrieved XLPE and CPE liners as was the case in our study for overall damage scores. With respect to specific damage modes, XLPE demonstrated more abrasion and scratches than CPE in this study, whereas CPE had more burnishing. This is similar to the findings by Salineros et al. [29]. XLPE has a lower wear rate that prolongs the longevity of the articular surface from third-body debris, whereas CPE has a higher wear rate that tends to smooth out scratches through removal of surface material. Longer-term studies are required to investigate the effect of crosslinking on fatigue resistance [1, 2, 13].

With respect to the quantitative measurements of wear, our findings were similar to those of other studies comparing the wear rate of XLPE and CPE [14, 25, 33]. Micro-

Table 2. Damage scoring

Variable	XLPE	CPE	p value
Total damage score	13 ± 4	16 ± 5	0.32
Damage score over bearing surface	9 ± 4	12 ± 4	0.51
Damage score over the rim	2 ± 1	2 ± 2	0.15
Backside damage score	2 ± 4	3 ± 3	0.73

The data are given as mean ± SD; XLPE = highly crosslinked polyethylene; CPE = conventional polyethylene.

Table 3. Micro-CT measurements

Variable	XLPE	CPE	p value
Articular deviation	0.30 ± 0.50 mm	1.12 ± 1.25 mm	0.042
Articular rate	0.05 ± 0.07 mm/year	0.18 ± 0.09 mm/year	0.003
Backside deviation	0.08 ± 0.13 mm	0.22 ± 0.21 mm	0.042
Rim deviation	0.14 ± 0.18 mm	0.58 ± 0.50 mm	0.009
Articular volume	82 ± 134 mm^3	350 ± 342 mm^3	0.017

The data are given as mean ± SD; XLPE = highly crosslinked polyethylene; CPE = conventional polyethylene; Articular deviation = head penetration at the apex of the liner; Rim deviation = maximum penetration around the rim.

CT has been validated for assessing polyethylene damage in retrieval studies, and this technique can examine the surface geometry at high resolution without destroying the implant [3, 31, 32]. Although there was no difference in damage scores between the XLPE and CPE groups, the CPE group had a three times greater wear rate (odds ratio, 3.1; confidence interval, 2.3–5.1) (as measured by micro-CT). There was no correlation between the penetration rates and damage scores. Therefore, damage scoring may not correlate with wear, and one should be circumspect using damage scores as a surrogate marker for wear. However, damage scores do provide additional, useful data beyond the quantitative micro-CT measurements of wear, specifically relating to the damage modes that occurred while the implant was in situ.

In summary, XLPE demonstrated less wear than CPE based on quantitative measurements provided by micro-CT, which was not apparent using damage scoring alone. Longer-term studies are required to determine the effect on implant longevity, but the superior wear properties of XLPE found in this study support its clinical use.

References

1. Baker DA, Bellare A, Pruitt L. The effects of degree of cross-linking on the fatigue crack initiation and propagation resistance of orthopedic-grade polyethylene. *J Biomed Mater Res A.* 2003;66:146–154.
2. Baker DA, Hastings RS, Pruitt L. Study of fatigue resistance of chemical and radiation crosslinked medical grade ultrahigh molecular weight polyethylene. *J Biomed Mater Res.* 1999;46:573–581.
3. Bowden A, Kurtz S, Edidin A. Validation of a micro-CT technique for measuring volumetric wear in retrieved acetabular liners. *J Biomed Mater Res.* 2005;75:205–209.
4. Bradford L, Baker DA, Graham J, Chawan A, Ries MD, Pruitt LA. Wear and surface cracking in early retrieved highly cross-linked polyethylene acetabular liners. *J Bone Joint Surg Am.* 2004;86:1271–1282.
5. Bradford L, Baker D, Ries MD, Pruitt LA. Fatigue crack propagation resistance of highly crosslinked polyethylene. *Clin Orthop Relat Res.* 2004;429:68–72.
6. Bradford L, Kurland R, Sankaran M, Kim H, Pruitt LA, Ries MD. Early failure due to osteolysis associated with contemporary highly cross-linked ultra-high molecular weight polyethylene. A case report. *J Bone Joint Surg Am.* 2004;86:1051–1056
7. Bragdon CR, Doerner M, Martell J, Jarrett B, Palm H; Multicenter Study Group, Malchau H. The 2012 John Charnley Award: Clinical multicenter studies of the wear performance of highly crosslinked remelted polyethylene in THA. *Clin Orthop Relat Res.* 2013;471:393–402.
8. Clohisy JC, Calvert G, Tull F, McDonald D, Maloney WJ. Reasons for revision hip surgery: a retrospective review. *Clin Orthop Relat Res.* 2004;429:188–192.
9. Digas G, Kärrholm J, Thanner J, Malchau H, Herberts P. The Otto Aufranc Award. Highly cross-linked polyethylene in total hip arthroplasty: randomized evaluation of penetration rate in cemented and uncemented sockets using radiostereometric analysis. *Clin Orthop Relat Res.* 2004;429:6–16.
10. Dumbleton JH, Manley MT, Edidin AA. A literature review of the association between wear rate and osteolysis in total hip arthroplasty. *J Arthroplasty.* 2002;17:649–661.
11. Estok DM 2nd, Bragdon CR, Plank GR, Huang A, Muratoglu OK, Harris WH. The measurement of creep in ultrahigh molecular weight polyethylene: a comparison of conventional versus highly cross-linked polyethylene. *J Arthroplasty.* 2005;20:239–243.
12. Estok DM 2nd, Burroughs BR, Muratoglu OK, Harris WH. Comparison of hip simulator wear of 2 different highly cross-linked ultra high molecular weight polyethylene acetabular components using both 32- and 38-mm femoral heads. *J Arthroplasty.* 2007;22:581–589.
13. Fisher J, McEwen HM, Tipper JL, Galvin AL, Ingram J, Kamali A, Stone MH, Ingham E. Wear, debris, and biologic activity of cross-linked polyethylene in the knee: benefits and potential concerns. *Clin Orthop Relat Res.* 2004;428:114–119.
14. Glyn-Jones S, McLardy-Smith P, Gill HS, Murray DW. The creep and wear of highly cross-linked polyethylene: a three-year randomised, controlled trial using radiostereometric analysis. *J Bone Joint Surg Br.* 2008;90:556–561.
15. Goldsmith AA, Dowson D, Wroblewski BM, Siney PD, Fleming PA, Lane JM. The effect of activity levels of total hip arthroplasty patients on socket penetration. *J Arthroplasty.* 2001;16:620–627.
16. Harris WH. The problem is osteolysis. *Clin Orthop Relat Res.* 1995;311:46–53.
17. Kurtz SM. *UHMWPE Biomaterials Handbook: Ultra-high Molecular Weight Polyethylene in Total Joint Replacement and Medical Devices*. 2nd ed. London, UK: Academic Press; 2009:43.
18. Kurtz SM, Gawel HA, Patel JD. History and systematic review of wear and osteolysis outcomes for first-generation highly cross-linked polyethylene. *Clin Orthop Relat Res.* 2011;469:2262–2277.
19. Kurtz SM, Hozack W, Turner J, Purtill J, MacDonald D, Sharkey P, Parvizi J, Manley M, Rothman R. Mechanical properties of retrieved highly cross-linked crossfire liners after short-term implantation. *J Arthroplasty.* 2005;20:840–849.
20. Kuzyk PR, Saccone M, Sprague S, Simunovic N, Bhandari M, Schemitsch EH. Cross-linked versus conventional polyethylene for total hip replacement: a meta-analysis of randomised controlled trials. *J Bone Joint Surg Br.* 2011;93:593–600.
21. Mall NA, Nunley RM, Zhu JJ, Maloney WJ, Barrack RL, Clohisy JC. The incidence of acetabular osteolysis in young patients with conventional versus highly crosslinked polyethylene. *Clin Orthop Relat Res*. 2011;469:372–381.
22. Maloney WJ, Galante JO, Anderson M, Goldberg V, Harris WH, Jacobs J, Kraay M, Lachiewicz P, Rubash HE, Schutzer S, Woolson ST. Fixation, polyethylene wear, and pelvic osteolysis in primary total hip replacement. *Clin Orthop Relat Res.* 1999;369:157–164.
23. Manning DW, Chiang PP, Martell JM, Galante JO, Harris WH. In vivo comparative wear study of traditional and highly cross-linked polyethylene in total hip arthroplasty. *J Arthroplasty.* 2005;20:880–886.
24. Martell JM, Verner JJ, Incavo SJ. Clinical performance of a highly cross-linked polyethylene at two years in total hip arthroplasty: a randomized prospective trial. *J Arthroplasty.* 2003;18:55–59.
25. McCalden RW, MacDonald SJ, Rorabeck CH, Bourne RB, Chess DG, Charron KD. Wear rate of highly cross-linked polyethylene in total hip arthroplasty. A randomized controlled trial. *J Bone Joint Surg Am.* 2009;91:773–782.
26. Muratoglu OK, Bragdon CR, O'Connor DO, Jasty M, Harris WH. A novel method of cross-linking ultra-high-molecular-weight polyethylene to improve wear, reduce oxidation, and retain mechanical properties. Recipient of the 1999 HAP Paul Award. *J Arthroplasty*. 2001;16:149–160.

27. Paterson NR, Teeter MG, MacDonald SJ, McCalden RW, Howard JL, Naudie DD. Highly cross-linked vs conventional polyethylene: no differences in rim notching from micromotion on retrieved acetabular liners. *J Arthroplasty*. 2012;27:1616–1621.
28. Paterson NR, Teeter MG, MacDonald SJ, McCalden RW, Naudie DD. The 2012 Mark Coventry award: A retrieval analysis of high flexion versus posterior-stabilized tibial inserts. *Clin Orthop Relat Res*. 2013;471:56–63.
29. Salineros MJ, Crowninshield RD, Laurent M, Wimmer MA, Jacobs JJ. Analysis of retrieved acetabular components of three polyethylene types. *Clin Orthop Relat Res*. 2007;465:140–149.
30. Schroder DT, Kelly NH, Wright TM, Parks ML. Retrieved highly crosslinked UHMWPE acetabular liners have similar wear damage as conventional UHMWPE. *Clin Orthop Relat Res*. 2011;469:387–394.
31. Teeter MG, Naudie DD, Charron KD, Holdsworth DW. Highly cross-linked polyethylene acetabular liners retrieved four to five years after revision surgery: a report of two cases. *J Mech Behav Biomed Mater*. 2010;3:464–469.
32. Teeter MG, Naudie DD, Charron KD, Holdsworth DW. Three-dimensional surface deviation maps for analysis of retrieved polyethylene acetabular liners using micro-computed tomography. *J Arthroplasty*. 2010;25:330–332.
33. Thomas GE, Simpson DJ, Mehmood S, Taylor A, McLardy-Smith P, Gill HS, Murray DW, Glyn-Jones S. The seven-year wear of highly cross-linked polyethylene in total hip arthroplasty: a double-blind, randomized controlled trial using radiostereometric analysis. *J Bone Joint Surg Am*. 2011;93:716–722.