Retrieved Highly Crosslinked UHMWPE Acetabular Liners Have Similar Wear Damage as Conventional UHMWPE

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Abstract

Background Highly crosslinked UHMWPE is associated with increased wear resistance in hip simulator and clinical studies. Laboratory and case studies, however, have described rim fracture in crosslinked acetabular liners. Controversy exists, therefore, on the relative merits of crosslinked liners over conventional liners in terms of wear performance versus resistance to fatigue cracking.

Questions/purposes We asked whether crosslinked liners would show less surface damage than conventional liners but would be more susceptible to fatigue damage.

Methods We examined 36 conventional UHMWPE and 39 crosslinked UHMWPE retrieved implants with similar patient demographics and identical design for evidence of wear damage, including articular surface damage, impingement, screw-hole creep, and rim cracks.

Results We observed no difference in wear damage scores for the two liners. Conventional liners more frequently impinged but were more often elevated with smaller head sizes. We observed creep in approximately 70% of both types of liners. Incipient rim cracks were found in five crosslinked liners, and one liner had a rim

fracture. Only one conventional liner had an incipient rim crack.

Conclusions Contrary to our expectation, damage was similar between crosslinked and conventional UHMWPE liners. Moreover, the 15% occurrence (six of 39) of incipient or complete fractures in crosslinked liners as compared with a 3% occurrence (one of 36) in conventional liners may have implications for the long-term performance of crosslinked liners. Longer-term studies will be necessary to establish the fate of rim cracks and thus the overall clinical fatigue performance of crosslinked liners.

Introduction

Highly crosslinked UHMWPE is the most commonly used bearing material in THA, consisting of 75% of the acetabular liners used in the United States as of 2008 [19]. Several studies show crosslinked UHMWPE has enhanced resistance to wear in hip simulator testing compared with conventional UHMWPE [8, 20, 21]. The improved wear resistance has been confirmed in clinical studies using radiographic evaluations showing reductions in wear compared with conventional, noncrosslinked UHMWPE at up to 5 years average followup [3, 7, 18].

However, crosslinking can decrease the mechanical properties of UHMWPE, including yield and ultimate tensile strengths, elongation to failure, and fatigue crack propagation resistance [10, 26]. Reports of crosslinked liner fracture in retrieved components have increased concerns about the adverse effects of crosslinking on mechanical properties [11, 29]. Although these reports described the fracture of small numbers of retrieved components, they did not examine a similar cohort of conventional liners.

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We (1) asked whether retrieved crosslinked acetabular liners would show less articular surface wear damage than retrieved conventional UHMWPE counterparts; and (2) sought to confirm reports of fatigue damage and cracking in the crosslinked group.

Materials and Methods

From our large, ongoing, Institutional Review Board-approved implant retrieval system, we identified 79 conventional UHMWPE (Trilogy; Zimmer Inc, Warsaw, IN) and 78 highly crosslinked liners (Longevity; Zimmer Inc) collected from revision surgeries at our institution. From these groups, 39 highly crosslinked liners were chosen randomly and then 36 conventional liners were matched so that the groups would be similar in regard to average demographic data. Demographic information was gathered from the patient records and included age at revision, length of implantation, indication for revision, and body mass index (BMI). Patient BMI, the length of implantation, and the average burnishing damage score for the crosslinked and conventional UHMWPE liners were compared using the independent samples t-test to ensure comparability of the groups. There was no difference in the demographic variables between the crosslinked and conventional UHMWPE groups (Table 1). The three leading diagnoses at revision were instability, osteolysis/loosening, and infection in both groups (Table 2). The femoral head diameters differed between the groups with smaller diameter heads used in the conventional UHMWPE liners (Table 3). Fisher's exact test comparing the frequency of use of the two most common head sizes (28 mm in conventional and 32 mm in cross-linked) confirmed the difference in head sizes between the groups ($p < 0.001$). Liner thickness at the pole was collected from the manufacturer based on the shell outer diameter (OD) and the polyethylene liner inner diameter. The most frequently used couple in the conventional group was a 50/52/54-mm OD shell with a 28-mm femoral head, yielding a thickness of 7.2 mm in 12 of 36 cases (33%) followed by a 58-mm OD shell with a 28-mm head for a thickness of 9.3 mm (four of 36 cases [11%]). In the crosslinked group, the most commonly used shell had an OD of 50/52/54 mm. It was used with a 32-mm head (thickness

of 6.3 mm) in nine of 39 implants (23%) and with a 28-mm head (thickness of 7.2 mm) in eight of 39 cases (10%). There were more than 10 other combinations, but these were used in three cases or fewer. The overall range of thicknesses was 5.3 mm to 16.3 mm in the conventional group and 6.3 mm to 12.3 mm in the crosslinked group. A Mann-Whitney rank sum test showed no difference in thickness between the groups ($p = 0.051$). Twenty-eight of the 36 conventional UHMWPE liners (78%) had an elevated rim, but only 15 of the 39 crosslinked liners (38%) had an elevated rim.

The conventional UHMWPE and crosslinked designs are of the same geometry and differ only by material. The liners are a full hemisphere with a polyethylene groove that interfaces with a metal locking ring on the acetabular shell. Conventional UHMWPE was defined as polyethylene for which no formal crosslinking or free-radical reduction process had been used [17]. The retrieved conventional UHMWPE liners were produced from calcium-stearate-free GUR 1050 resin machined from compression-molded sheet polyethylene. The final liner was sterilized with gamma radiation (25 kGy) in an inert nitrogen environment.

Table 2. Indication for revision

Indication for revision	UHMWPE	Crosslinked
Instability	20 (56%)	19 (49%)
Osteolysis/loosening	7 (19%)	10 (26%)
Infection	6 (17%)	6 (15%)
Polyethylene wear	1 (3%)	1 (3%)
Periprosthetic fracture	1 (3%)	2 (5%)
Malpositioning	—	1 (3%)
Unknown	1 (3%)	—

Table 3. Head size

Head size	UHMWPE	Crosslinked
22 mm	5 (14%)	—
26 mm	2 (6%)	—
28 mm	25 (69%)	15 (38%)
32 mm	4 (11%)	21 (54%)
36 mm	—	2 (5%)
40 mm	—	1 (3%)

Table 1. Demographic data

Type of liner	Females		LOI (years)		Age at revision (years)		BMI (kg/m ²)	
	Number (%)	p	Average (range)	p	Average (range)	p	Average (range)	p
UHMWPE (n = 36)	22 (61%)	0.392	2.30 (0.04–5.62)	0.295	68 (13–86)	0.156	27 (15–39)	0.559
Crosslinked (n = 39)	20 (51%)		1.90 (0.03–6.99)		63 (17–87)		27 (19–43)	

LOI = length of implantation; BMI = body mass index.

The retrieved crosslinked liners were also manufactured from calcium-stearate-free GUR 1050 resin compression-molded sheets. Before machining, the compression-molded sheet was subjected to electron-beam irradiation of 100 kGy to attain crosslinking and was then melted to reduce free-radicals. The final liners were sterilized with use of a gas-plasma technique [5].

Components were received from the pathology department and then underwent standard handling consisting of cleaning in 10% bleach solution and detergent and then entry into the retrieval database.

Visual wear damage grading of the articular surface was performed by two independent graders (DTS, NHK) by direct visualization and by light stereomicroscopy (up to 31 $\times$). The articular surfaces were subjectively graded for abrasion, burnishing, cracking, delamination, pitting, plastic deformation, third body debris, and scratching using a 0 to 3 scale as described by Hood et al. [14]. In this scale, a grade of 0 represents no wear damage; 1 represents damage over less than 10% of the surface; 2 represents damage involving 10% to 50%; and 3 represents damage over more than 50% of the surface area. Interrater reliability of the summed visual damage scores of the two observers was excellent with a value of 0.904; however, grading was averaged if a discrepancy was found. Liners were divided into quadrants with the elevated rim, when present, to the left and the quadrants labeled in a clockwise fashion beginning in the upper left hand corner (Fig. 1) [1]. When an elevated rim was not present, liners were divided into quadrants based on the location of the etchings. Each quadrant was scored separately. The maximum possible wear damage score was 96 (four quadrants $\times$ eight damage modes $\times$ maximum score of 3). A previously described damage mode termed “furrowing” was noted when present [5].

Fig. 1 A schematic of the grading quadrants is shown. When an elevated rim was present, it was placed to the left and quadrants were numbered clockwise from the upper left corner. When no elevated rim was present, numbering was based off of the etchings on the liner.

Impingement was defined as polyethylene wear damage and surface deformation on the rim of the component based on visual and stereomicroscopic examination and was graded in the same quadrant system. Two observers (DTS, NHK) subjectively graded severity on a scale from 1 to 4: Grade 1 if minimal evidence of impingement was noted; Grade 2 when damage extended was less than 1 mm into the rim; Grade 3 when damage extended between 1 and 2 mm into the rim; and Grade 4 when damage extended greater than 2 mm into the rim [24]. For this measure, interobserver reliability was high in Quadrants 1 and 3 (kappa value of 0.752 and 1.00, respectively) but only moderate in Quadrants 2 and 4 (0.476 and 0.586, respectively). When a discrepancy in grades was found, both observers regraded and came to a consensus score. Cracks in the rim were visualized with a stereomicroscope using indirect illumination. This technique involves directing the light source perpendicular to the rim of the liner from the inside surface and examining the rim for evidence of cracks. The cracks appear as bright lines within the antirotation scallops in the rim of the liner. Cracks were graded at the same time by two observers (DTS, NHK) and no cracking was recorded unless both observers agreed that it was present.

Plastic deformation (creep) on the backside of the polyethylene liner into empty screw holes in the metallic acetabular shell was evaluated in four quadrants for location and severity. This damage was confirmed as creep rather than wearing away of the material around the screw hole because machining marks were still visible on the backside around the areas of creep. Two observers (DTS, NHK) subjectively graded severity on a 0 to 2 scale. A Grade of 0 was given when no visual evidence of creep was observed, Grade 1 when visual evidence was observed but no palpable change in height could be felt between the affected and unaffected regions, and Grade 2 when both visual evidence and a palpable step was noted [16]. Interrater reliability was excellent in all quadrants with kappa values ranging from 0.869 to 0.940.

Two orthopaedic surgeons (DTS, MLP) measured the inclination angle of the acetabular component from the AP pelvic radiograph most closely preceding the revision surgery. The interrater reliability was excellent with a value of 0.997. Inclination angle was measured by creating a horizontal line between bony landmarks on the pelvis and then measuring the angle of the cup in relation to that line [25]. Radiographs were available for all 39 of the cases with crosslinked liners and in 34 of the 36 cases with conventional UHMWPE liners. The average inclination angle was 46° in the crosslinked group and 47° in the conventional UHMWPE group and was similar ($p = 0.74$) between the groups.

The average wear damage, radiographic inclination angle, and average damage scores for the damage modes

pitting, scratching, third body debris, and plastic deformation were compared using the Mann-Whitney rank sum test. For burnishing, the average damage score was compared using a t-test. A one-way analysis of variance was used to examine the average summed damage scores based on reason for revision for both crosslinked and conventional UHMWPE liners followed by a Holm-Sidak post hoc analysis. Correlations in head size and wear damage and liner thickness and wear damage were examined with a Pearson correlation when the data were normal and had constant variance and with Spearman rank order correlation when it was not.

Results

The total average wear damage score for the articular surface was 24.8 (range, 13–40) for the conventional UHMWPE group and 22.6 (range, 12–38) for the crosslinked group. The scores for the two groups were similar ($p = 0.082$). Articular surface wear damage modes were most commonly burnishing, pitting, and scratching with no differences in damage modes between materials (Table 4). Articular surface cracking or delamination was not seen in either group. We found furrowing on the articular surface of 15 of the 39 (38%) crosslinked liners (Fig. 2) and in none of the conventional UHMWPE liners. Average wear damage grades based on reason for revision were different in both groups (Table 5). Crosslinked liners revised for

osteolysis and loosening had higher wear damage scores than those revised for instability ($p = 0.003$) but were not higher than those revised for infection ($p = 0.056$). Conventional UHMWPE liners revised for osteolysis and loosening had higher wear scores than those revised for instability ($p = 0.010$) and liners revised for infection had higher wear damage scores than those revised for instability as well ($p = 0.017$). No correlation was found between head size and articular surface wear damage in either group (conventional $p = 0.166$, crosslinked $p = 0.366$). There were also no correlations found between liner thickness at the pole and wear damage in either group (conventional $p = 0.230$, cross-linked $p = 0.312$). Screw hole creep could not be graded in three of the conventional UHMWPE liners as a result of the liner being locked or cemented into the metallic shell. Of the remaining 33 conventional UHMWPE liners, 25 (76%) exhibited screw hole creep. Creep was isolated to one quadrant in 24% of the liners, two quadrants in 40%, three quadrants in 12%, and was located in all four quadrants in 24% of the liners. The most severe area of screw hole creep was Grade 1 (visible, but not palpable) in 32% and was Grade 2 (palpable) in 68% of the conventional UHMWPE liners. Screw hole creep was graded in all 39 of the crosslinked liners and was present in 29 (74%). Creep was found in only one quadrant in 21%, in two quadrants in 52%, in three quadrants in 7%, and in all four quadrants in 21% of the liners. The most severe area of creep was Grade 1 in 55% of liners and Grade 2 in 45%. Rim impingement was present in 25

Table 4. Average wear damage scores by damage mode

Wear mode	UHMWPE	Crosslinked	p
Burnishing	8.1	7.2	0.09
Pitting	7.4	6.1	0.06
Scratching	8.1	8.5	0.57
Third body debris	0.4	0.3	0.63
Plastic deformation	0.3	0.4	0.77
Abrasion	0.6	0.05	0.63

Table 5. Average damage score by reason for revision

Reason for revision	Conventional UHMWPE Average damage score $\pm$ SD	Crosslinked UHMWPE Average damage score $\pm$ SD
Infection	29.7 $\pm$ 6.3	21.7 $\pm$ 3.3
Osteolysis/loosening	28.7 $\pm$ 6.8	26.4 $\pm$ 4.9
Instability	22.4 $\pm$ 5.2	20.6 $\pm$ 4.8

Fig. 2A–B (A) A photomicrograph at $\times 12$ and (B) a scanning electron micrograph of furrowing on the articular surface of a crosslinked polyethylene liner are shown.

of 36 (69%) of the conventional liners and in 17 of 39 (44%) of the crosslinked liners. Of those liners that impinged in the conventional UHMWPE group, 84% had an elevated rim. In the crosslinked group, those that impinged had elevated rims in 41% of liners. The majority of the implants had impinged in only one location (68% and 71% for conventional and crosslinked, respectively). The impingement lesion was mild to moderate (Grade 1 or 2) in 84% of conventional liners and 82% of crosslinked liners and more severe (Grade 3 or 4) in 16% of conventional liners and 18% of crosslinked liners.

Cracking of the rim was present in five (13%) of the crosslinked liners and one (3%) of the conventional UHMWPE liners (Fig. 3). One crosslinked liner had gross fracture of the rim (Fig. 4). The liner that fractured was revised for subluxation and mild instability, and the fracture was described in the operative note at revision as being located in the anterosuperior portion of the liner. Symmetric indentations within the antirotation scallops adjacent to the prominent metal on the rim of the metallic shell were noted in both groups (Fig. 5).

Fig. 3 A photomicrograph of a backlit liner shows an incipient rim crack within the scalloped region (black arrow) taken at $\times 15$.

Discussion

Although crosslinked liners have displayed lower wear rates in hip simulator and clinical studies when compared with conventional polyethylene [8, 20, 21], they also display decreased fracture toughness [10, 26]. Highly crosslinked polyethylene is currently the most common bearing surface used in THA [19] and recent reports of cracking and fracture of the rims have increased concern regarding its longevity [11, 29]. We sought to examine the wear damage and fatigue damage of a cohort of polyethylene liners with identical design that differed only by material. We (1) asked whether retrieved crosslinked acetabular liners would show less articular surface wear damage than retrieved conventional UHMWPE liners; and (2) sought to confirm reports of fatigue damage and cracking in the crosslinked group.

Our study has limitations. First, a retrieval study necessarily uses a cohort of failed implants, not those that

Fig. 5 A photomicrograph showing symmetric notching within the antirotation scallops of the rim (white arrows) taken at $\times 15$ is shown.

Fig. 4A–B (A) A digital image and (B) photomicrograph magnification of the fractured liner rim taken at $\times 6$ are shown.

function well, and one cannot presume some of the observations might not also occur with some well-functioning implants. Nevertheless, information from failed implants can provide useful information about clinical performance. Second, the femoral heads articulating with crosslinked liners were larger than those articulating with conventional UHMWPE liners. This may be the result of the increasing use of larger femoral heads, as confidence in crosslinked liner wear resistance has grown, to attain greater ROM and stability. The use of larger heads may increase wear damage, which could artificially increase the amount of damage in crosslinked liners. However, we found no correlation between head size and wear damage in either group. Third, impingement lesions were more prevalent in the conventional UHMWPE group compared with the crosslinked liners. This is probably because there were more elevated rims in the conventional group and may reflect a trend toward nonelevated liners in more recent cases. The increased frequency of impingement in the conventional group could have adversely affected the wear damage. Finally, we did not attempt to make measurements of the thickness of the liners as a method of determining wear. Such measurements, however, lack accuracy and suffer from the required assumption of an initial thickness for the liner. Nonetheless, differential thickness measurements between the most and least worn liners would have allowed comparison of this thickness differential with our wear damage scores cups between the most and least worn walls of the cups.

We asked whether crosslinked liners would display less articular surface wear damage than conventional UHMWPE liners. Visual wear damage grading of retrieved acetabular liners did not show a difference in either the type of wear damage modes or their severity. The exception was the presence, in the crosslinked liners only, of furrowing on the articular surface. More investigation into this wear damage mode is needed to understand the mechanism behind this damage mode, perhaps by associating the pattern with the mechanical properties and failure of crosslinked UHMWPE. No difference was found in the incidence of rim impingement and backside screw hole creep; these forms of damage were common in both types of liners. When implants from both groups were pooled, 56% demonstrated evidence of impingement. This prevalence agrees with the work of Shon et al. who examined 170 retrieved acetabular components and found that 96 (56%) had rim damage consistent with impingement [28]. Furthermore, they identified that an elevated rim increased the frequency of impingement [28]. We found conventional UHMWPE implants were more often elevated and showed more frequent evidence of impingement. Crosslinking clearly reduces wear rates in hip simulator tests [2, 12, 15, 21] (though wear rates are higher under impingement

conditions [13]). However, in our study, the amount of wear damage was similar between crosslinked and conventional UHMWPE liners. This seems paradoxical, but qualitative grading of wear damage does not necessarily correlate with wear rate. We did not attempt to measure wear rate in this cohort for several reasons. First, some patients in our cohort did not have their primary surgery at our institution, so we did not have access to serial radiographs to measure head penetration rates. Another method to determine wear rate involves measuring the dimensions of the retrieved liner and comparing this with an assumed original dimension. This was not performed as a result of the difficulty and questionable quality of the volume estimation based on an assumption of original dimensions. Published *in vivo* wear data from radiographic analyses show reduction in head penetration into crosslinked liners compared with conventional liners [3, 6, 27]. Studies of greater than 5 years describe a wearing-in period of the implant, usually over the first 2 years [3, 18], but Digas et al. observed a change in femoral head penetration in the first 2 years of implantation time between crosslinked and conventional UHMWPE liners, suggesting a difference should exist in wear damage, even with short followup [6]. McCalden et al. showed a difference in mean head penetration with conventional liners compared with the crosslinked liners at 6.8 years followup (0.003 mm/year versus 0.051 mm/year) [18]. However, at early followup, one would expect a smaller difference in wear quantitatively with early “bedding in” of the head into the crosslinked liner over the first year of implantation [3]. Previous studies have presented evidence of crosslinked liners having a “shape memory” such that machining marks can be recovered after remelting of the liners [22–24]. We did not perform remelting on the liners in this study but plan to perform this analysis in the future. This “shape memory” is not entirely clear; another study performed in our laboratory did not observe the same return of machining marks [17]. We hypothesized that the difference in results could be the result of the relatively short implantation and simulation times in the studies by Muratoglu et al. compared with the severe impingement simulation that we performed [17, 22–24]. The implantation times of the retrieved crosslinked liners in our current study were greater than those of Muratoglu et al., so determining the recoverability of the damage seen in this cohort is of interest.

Incipient rim cracks in crosslinked liners were more often noted, and one crosslinked liner had gone on to fracture. The fracture surface had fine striations that were perpendicular to the direction of crack growth, which is consistent with the pattern found in the literature for highly crosslinked UHMWPE fatigue testing specimens [4, 10, 26] and in an analysis of rim fracture in retrieved liners [9].

The case studies of rim fracture in the literature reported a similar fracture pattern and appearance [11, 29]. Furthermore, the presence of incipient rim cracks in five (13%) of the crosslinked liners as compared with only one (3%) of the conventional UHMWPE liners may be a cause for concern. Although rim cracks may not all propagate to fracture, the fact that some have is troublesome; to our knowledge, no reports exist of fracture of this design in conventional UHMWPE liners. The symmetric indentations within the antirotation scallops of the liner are likely to the result of rotational motion at the liner-metal implant interface.

We found no difference in wear damage between conventional UHMWPE and crosslinked liners of an identical design. This is an unexpected finding given the superior wear resistance of crosslinked UHMWPE. We also found a propensity for cracking and rim fracture in the crosslinked group, which is in keeping with the reduced fatigue properties of crosslinked liners. Rim fracture may continue to be a clinical problem because rim cracks appear to be a source of complete rim fracture and possible dissociation. In future studies, a combination of retrieval analysis and clinical wear measurements could shed light on the apparent dichotomy between surface damage and wear rates.

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