Wear rates of highly cross-linked polyethylene humeral liners subjected to alternating cycles of glenohumeral flexion and abduction

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**Background:** Although short-term outcomes of reverse total shoulder arthroplasty have been promising, long-term success may be limited due to device-specific complications, including scapular notching. Scapular notching has been explained primarily as mechanical erosion; however, the generation of wear debris may lead to further biologic changes contributing to the severity of scapular notching.

**Methods:** A 12-station hip simulator was converted to a reverse total shoulder arthroplasty wear simulator subjecting conventional and highly cross-linked ultra-high-molecular-weight polyethylene humeral liners to 5 million cycles of alternating abduction-adduction and flexion-extension loading profiles.

**Results:** Highly cross-linked polyethylene liners (36.5 ± 10.0 mm\textsuperscript{3}/million cycle) exhibited significantly lower volumetric wear rates compared with conventional polyethylene liners (83.6 ± 20.6 mm\textsuperscript{3}/million cycle; \(P < .001\)). The flexion-extension loading profile exhibited significantly higher wear rates for conventional (\(P < .001\)) and highly cross-linked polyethylene (\(P < .001\)) compared with the abduction-adduction loading profile. Highly cross-linked wear particles had an equivalent circle diameter significantly smaller than wear particles from conventional polyethylene (\(P < .001\)).

**Conclusions:** Highly cross-linked polyethylene liners significantly reduced polyethylene wear and subsequent particle generation. More favorable wear properties with the use of highly cross-linked polyethylene may lead to increased device longevity and fewer complications but must be weighed against the effect of reduced mechanical properties.

**Level of evidence:** Basic Science, Biomechanics.

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**Keywords:** Reverse total shoulder arthroplasty; in vitro wear simulation; highly cross-linked polyethylene; wear particle analysis; scapular notching
still prone to numerous complications, including aseptic loosening \(^{10,11,37}\) and scapular notching. \(^{37}\)

Aseptic loosening, caused by osteolysis of periprosthetic bone, was reported as the leading reason for revision of rTSA prostheses in a review of the Norwegian Arthroplasty Register (13 of 36 revisions [36.1%]). \(^{11}\) Retrieved rTSA humeral liner components have also illustrated the severity of ultra-high-molecular-weight polyethylene (UHMWPE) damage capable of producing polyethylene wear particles. \(^{6,19}\) Terrier et al \(^{32}\) calculated volumetric UHMWPE wear rates for reverse prostheses that were nearly 5 times higher than those calculated for anatomic prostheses in a finite-element model and cited the need for further experimental and clinical evaluation.

Scapular notching, reported by Sirveaux et al. \(^{31}\) is described as bony erosion of the glenoid neck with a postoperative incidence of 0% to 92%. \(^{3,5,9,14,15,31}\) Scapular notching has been shown to negatively affect clinical outcomes. \(^{7,30,31}\) Nyffeler et al. \(^{32}\) first proposed that the biomechanical explanation may only partially contribute to scapular notching, suggesting that particle-induced osteolysis caused by UHMWPE wear may also be a contributing factor. This hypothesis has not been confirmed but has received increasing attention as a plausible explanation for the progression of scapular notching past the inferior baseplate screw. \(^{3,4,16,22}\)

In total hip arthroplasty (THA), wear particle-induced osteolysis has been well described as a potential source of bone loss and implant loosening. \(^{23,24}\) To overcome this, highly cross-linked UHMWPE has been used extensively in THA and has been associated with reduced wear rates, both in vitro and in vivo. \(^{25,27,28}\) Although rTSA shares a similar ball-in-socket design as THA, conventional UHMWPE continues to be the gold standard material in rTSA. The use of highly cross-linked UHMWPE humeral cups may similarly reduce wear rates in rTSA systems, potentially decreasing the rate of UHMWPE particle generation and wear particle-induced osteolysis. This may ultimately lessen the contribution of wear particle-induced osteolysis to aseptic loosening and scapular notching, potentially improving implant survival and clinical outcomes.

The purpose of this study was to investigate and characterize the wear performance and particle generation of highly cross-linked UHMWPE humeral cups in a rTSA wear simulation. Our hypotheses were that (1) highly cross-linked UHMWPE humeral liners would exhibit lower wear rates and volumetric wear compared with conventional UHMWPE liners and that (2) the number of wear particles and morphology would differ between highly cross-linked and conventional UHMWPE liners.

**Materials and methods**

**Test groups**

UHMWPE (GUR1050) was machined into custom 36-mm humeral liners and underwent material processing according to 2 different protocols. The first group of conventional UHMWPE underwent no further cross-linking treatment. The second group was cross-linked with 50-kGy gamma irradiation and post-irradiation annealing (Sterigenics, Willowbrook, IL, USA). Both groups were then sterilized with ethylene oxide before testing. Humeral liners were press-fit into testing fixtures (Fig. 1) and articulated against a 36-mm glenosphere (Zimmer Inc, Warsaw, IN, USA).

**In vitro wear simulation protocol**

A previously described wear simulation protocol developed at our institution was used \(^{34}\) in which a 12-station hip wear simulator (MTS Bionix, Eden Prairie, MN, USA) was converted to a rTSA wear simulator by modification of the fixture setup, loading profiles, and test protocol. Briefly, the simulation completed 5 million total cycles of simulated arm motion, alternating abduction-adduction (abd-add) and flexion-extension (flex-ext) loading profiles every 250,000 cycles. The loading profiles ranged from 20.0 N to 617.8 N (90% body weight) for abd-add and 20.0 N to 926.7 N (135% body weight) for flex-ext arm motion. This protocol was developed based on in vivo telemetric data reported by Bergmann et al. \(^{2}\) and agrees strongly with subsequent biomechanical studies on rTSA prostheses \(^{17,18}\) and analyses of rTSA glenohumeral contact forces. \(^{1,33}\)

Components remained immersed in individual glass bowls containing defined bovine calf serum (21 g protein/L). Lubrication fluid also contained 0.2% sodium azide, 7.0 \(\times\) \(10^{-3}\) g/mL ethylenediaminetetraacetic acid (Ricca Chemical, Arlington, TX, USA), and deionized water throughout testing. Before testing, UHMWPE liners were presoaked in lubrication fluid to account for fluid sorption that occurs during initial periods of liner immersion.

**Measurement of wear**

Every 250,000 cycles, UHMWPE humeral liners were removed from test fixtures, cleaned, and dried with nitrogen gas according to International Organization for Standardization (ISO) Standard 14242-2. Liners were then measured with a precision mass balance (A-200DS, 0.030-mg precision; Fisher Scientific, Pittsburgh, PA, USA) for determination of material lost at each interval. Uptake or loss of additional serum was accounted for by 4 load-
soak control stations. Load-soak components underwent axial joint compression but no dynamic rotational motion. Mass loss was then converted to volume loss by dividing by UHMWPE density and then converted to volumetric wear rate (mm³/million cycle) and linear wear rate (mm/million cycle) calculated from the glenosphere surface contact area.

Serum from all dynamic stations was thawed overnight at room temperature from 6 different time points throughout testing. Time points were after abd-add loading profile at 250,000 cycles, 2.25 million cycles, and 4.75 million cycles and after flex-ext loading profile at 500,000 cycles, 2.5 million cycles, and 5 million cycles. After the serum was thawed, proteins were digested by addition of 5.0 mol/L NaOH at 37°C with constant stirring. 

Digestion was passed through a 0.2-μm polycarbonate filter. Filters were sputtered with a thin film of Au-Pd before subjected to environmental scanning electron microscopy (Quanta FEG40; FEI, Hillsboro, OR, USA). Ten images were taken at random locations from each filter (original magnification x10,000) and then analyzed with a custom MATLAB program (MathWorks Inc, Natick, MA, USA) developed to characterize size and morphology of individual polyethylene particles. Particles were characterized by equivalent circle diameter \( [(4 \pi \times \text{area})^{1/2}] \), aspect ratio \( (d_{\text{max}}/d_{\text{min}}) \), and roundness \( (4 \pi \times \text{area} / d_{\text{max}}^2) \).

**Statistical analysis**

All statistical analyses were run with SigmaPlot software (Systat Software Inc, Chicago, IL, USA). Direct comparisons between particle characteristics were made using the Student \( t \) test, with significance set at \( P < .05 \). Volumetric wear rates and linear wear rates were compared using a 2-way analysis of variance with 2 factors: UHMWPE type and cycle number and UHMWPE type and motion profile, with significance set at \( P < .05 \).

**Results**

**In vitro wear simulation**

All stations successfully completed 5 million cycles of wear simulation, alternating abd-add and flex-ext loading profiles every 250,000 cycles. Total UHMWPE volume loss for each material is shown in Figure 2. At the conclusion of 5 million cycles of testing, conventional UHMWPE exhibited significantly higher total volume loss \( (418.1 \pm 43.8 \text{ mm}^3) \) than highly cross-linked UHMWPE \( (182.6 \pm 10.7 \text{ mm}^3); P < .001 \).

**Figure 2** Total volume loss of humeral cups is shown over 5 million cycles of reverse total shoulder arthroplasty wear simulation testing. Highly cross-linked polyethylene liners exhibited significantly less volume loss compared with the same humeral cups with conventional ultra-high-molecular-weight polyethylene (UHMWPE) liners \( (P < .001) \). The error bars show the standard deviation.

Conventional UHMWPE particles were also significantly more fibrillar than highly cross-linked polyethylene with respect to the particle aspect ratio \( (2.70 \pm 1.7 \text{ vs } 2.45 \pm 1.5; P < .001) \) and particle roundness \( (0.36 \pm 0.19 \text{ vs } 0.38 \pm 0.19; P < .001) \). Particle shape and morphology also varied by motion profile, as described in detail in Table I. Conventional UHMWPE particles displayed significant differences in the ECD and aspect ratio between abd-add and flex-ext profiles \( (P > .05) \). No significant difference in highly cross-linked UHMWPE \( (P > .05) \) was found for ECD, aspect ratio, or roundness between motion profiles.

**Discussion**

The superior wear properties of highly cross-linked UHMWPE liners have been previously illustrated in THA and in conventional TSA. Terrier et al used finite-element analysis to demonstrate that volumetric wear rates of conventional UHMWPE in rTSA were up to 5 times higher than anatomic TSA. Recent retrieval studies
have also highlighted the need for examining materials with lower wear rates in TSA and rTSA. In the current simulation, highly cross-linked UHMWPE demonstrated a significant reduction in wear compared with conventional UHMWPE components in the setting of rTSA. Similar to THA, a decrease in UHMWPE wear in rTSA devices may lead to an increase in device longevity, further decreasing the need for revision surgery and ultimately improving patient outcomes.

Scapular notching has been described as a defect of bone inferior to the glenosphere thought to be caused by mechanical impingement of the superomedial humeral component and medial humeral metaphysis with the remaining inferior pillar of bone of the glenoid. Although prosthetic impingement is most likely the cause for Nerot-Sirveaux grades 1 and 2 scapular notching, some have questioned whether purely biomechanical mechanisms can adequately explain grade 3 and 4 notching, where bone loss extends beyond the inferior baseplate screw. Intuitively, the humeral component would be unable to erode into the inferior glenoid past this screw. Owing to the presence of UHMWPE wear debris, the inflammatory environment that ultimately yields particle-induced osteolysis may contribute to the progression of scapular notching, and thus, a reduction in wear particles may help to prevent the progression of scapular notching. Future studies are warranted to further elucidate the role of particle generation and the potential effect on scapular notching.

Figure 3  Volumetric wear rate of humeral cups is shown over (left) 5 million cycles of wear simulation, and examining only 2.5 million cycles of the (middle) abduction-adduction loading profile and (right) the flexion-extension loading profile. The error bars show the standard deviation. UHMWPE, ultra-high-molecular-weight polyethylene.

Figure 4  Polyethylene wear particles isolated from test serum of (top) conventional polyethylene and (bottom) highly cross-linked polyethylene humeral liners.

Figure 5  Distribution of wear particle size for conventional and highly cross-linked ultra-high-molecular-weight polyethylene (UHMWPE).
Previous reports have demonstrated that the use of highly cross-linked UHMWPE leads to the generation of a lower concentration of phagocytosable wear particles in THA and TSA wear simulation. The current study suggests that this trend is also established in rTSA devices, because highly cross-linked UHMWPE exhibited a 54% reduction in the number of wear particles compared with conventional UHMWPE, with nearly all of the analyzed particles from both groups falling within the 0.1- to 1.0-µm phagocytosable range. Wear debris from highly cross-linked and conventional UHMWPE was fibrillar in shape and smaller than TSA debris, consistent with the previous rTSA wear study conducted at this institution and with previous studies. Highly cross-linked UHMWPE particles were significantly smaller and less fibrillar than conventional UHMWPE particles. Fibrillar particle morphology has been associated with increased inflammatory response, although the extent of this finding is unclear. These results suggest that highly cross-linked UHMWPE humeral liners generate fewer and potentially less inflammatory wear particles than conventional UHMWPE.

The limitations of the present study include the in vitro nature of the analysis. Any recommendations of bearing surface options for arthroplasty should be made after thorough biomechanical and clinical evaluation. The primary purpose of this study was to investigate the difference in wear behavior between conventional and highly cross-linked UHMWPE humeral liners with an established rTSA wear simulation. Although the reduced wear rate observed in the highly cross-linked UHMWPE was an expected result when in vitro hip wear simulations were used as a frame of reference, this represents the first in vitro comparison of conventional vs highly cross-linked polyethylene in the setting of rTSA. Further, this simulation contributes to the growing body of literature on the performance of UHMWPE under cross-shear conditions, which is likely to be more frequently encountered in the setting of rTSA.

Although cross-linked UHMWPE exhibited significant reductions in volumetric wear, it is important to note that the cross-linking process has been shown to negatively affect toughness and resistance to fracture. Nam et al also demonstrated that humeral liners often undergo rim loading and impingement, which may leave highly cross-linked UHMWPE components susceptible to crack initiation, propagation and, ultimately, failure. Currently, there is no literature discussing the potential effect of highly cross-linked polyethylene on rim damage and component fracture in the presence of device impingement. Further biomechanical studies should focus on characterizing the performance of cross-linked UHMWPE humeral liners under impingement conditions.

Table I

<table>
<thead>
<tr>
<th>Test group</th>
<th>Motion profile</th>
<th>Equivalent circle diameter (µm)</th>
<th>Aspect ratio</th>
<th>Roundness</th>
<th>P</th>
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</thead>
<tbody>
<tr>
<td>Conventional UHMWPE</td>
<td>Abduction-adduction</td>
<td>0.30 ± 0.13</td>
<td>2.74 ± 1.9</td>
<td>0.36 ± 0.19</td>
<td>.001</td>
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<tr>
<td></td>
<td>Flexion-extension</td>
<td>0.29 ± 0.09</td>
<td>2.68 ± 1.6</td>
<td>0.36 ± 0.20</td>
<td>.928</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>&lt;.001</td>
<td>.015</td>
<td>.378</td>
<td></td>
</tr>
<tr>
<td>Highly cross-linked UHMWPE</td>
<td>Abduction-adduction</td>
<td>0.25 ± 0.10</td>
<td>2.46 ± 1.5</td>
<td>0.38 ± 0.19</td>
<td>.330</td>
</tr>
<tr>
<td></td>
<td>Flexion-extension</td>
<td>0.25 ± 0.10</td>
<td>2.46 ± 1.5</td>
<td>0.38 ± 0.19</td>
<td>.946</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>.394</td>
<td>.497</td>
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</tbody>
</table>

UHMWPE, ultra-high-molecular-weight polyethylene.

* Particles were isolated from test serum at 3 time points per motion profile and averaged for final results. Data are shown as the mean ± standard deviation.

1 Statistically significant.

Conclusions

The results of this in vitro simulation indicate that the use of highly cross-linked humeral liners in rTSA leads to a significant reduction in UHMWPE component wear. With lower wear rates in vivo, particle-induced osteolysis and potentially implant loosening may be reduced. This may theoretically enhance the clinical survival of rTSA systems. However, the benefit of improved wear properties of highly cross-linked UHMWPE must always be weighed against reductions in dynamic mechanical properties, including fracture toughness and ultimate yield strength.

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