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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^3/million cycle) exhibited significantly lower volumetric wear rates compared with conventional polyethylene liners (83.6 ± 20.6 mm^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.

Keywords: Reverse total shoulder arthroplasty; in vitro wear simulation; highly cross-linked polyethylene; wear particle analysis; scapular notching

Investigational Review Board approval was not required for this study.

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Reverse total shoulder arthroplasty (rTSA) has been used with increasing frequency in the treatment of massive rotator cuff tears and chronic rotator cuff tear arthropathy. Although short-term clinical results are promising, rTSA is

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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[22] 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.[12,25,27,28] 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).

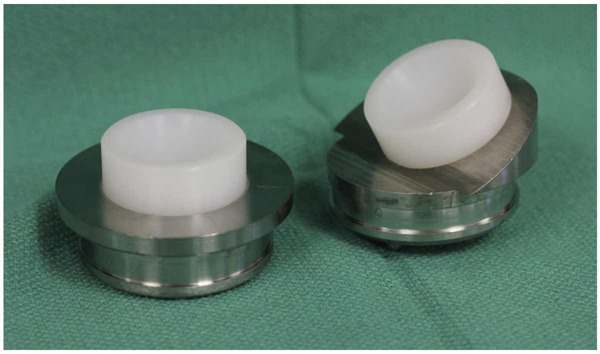

Figure 1 Humeral liner components press-fit into (left) abduction-adduction testing fixture and (right) flexion-extension testing fixture.

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, 7.0×10^{-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-