Tribological Performance of Bearing Materials for Hemiarthroplasty: An in Vitro Investigation Using Live Cartilage

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INTRODUCTION: Developing less invasive appoached for total joint replacement remains a key challenge in orthopedics. Hemiarthroplasty, which replaces only the damaged side of a joint while preserving the native cartilage on the opposing surface, aims to maintain joint function and delay the need for more extensive procedures. However, the long-term success of hemiarthroplasty depends on how well the implant material interacts with living cartilage under tribological conditions. Despite widespread use of cobalt-chromium (CoCr) alloys, concerns about harmful wear particle and ion release persist. In response, orthopedics research is turning to alternative materials, which have shown excellent tribological and biocompatible properties in total joint replacement. This study uses an in vitro cartilage wear model to evaluate these promising materials for hemi-arthroplasty, with the goal of informing future material selection for this procedure.

METHODS: CoCr, zirconia-toughened alumina (ZTA), and two variations of ultra-high molecular weight polyethylene (UHMWPE) were selected as bearing materials. The UHMWPE group included a conventional hydrophobic formulation and a hydrophilic variant obtained by O_2 plasma surface treatment. Bovine cartilage explants (14 × 20 mm) from the patellofemoral groove were paired with the bearing materials. A four-station joint simulator, carrying one ball of each material, applied physiological rolling–gliding motion under 2 MPa contact load onto the cartilage explants. Cell culture medium was used as lubricant and cartilage nourishment. Tests were conducted for 3 hours daily and five consecutive days for a total of about 27,000 cycles. Free-swelling controls (FSC) were maintained under identical handling conditions without loading. Cell culture medium was changed twice daily, immediately before and after the 3hr test. Post-experiment analyses included live/dead fluorescence imaging for chondrocyte viability, histological evaluation of matrix integrity, metabolic activity determination, and media analyses. Specifically, we conducted hydroxyproline quantification to assess collagen wear, and dimethylmethylene blue (DMMB) assay for sulfated glycosaminoglycan (sGAG) release from daily test samples. Wear rates for collagen and sGAG were then calculated from the slopes of release curves across five time points (Fig. 1). Each group was tested with cartilage from N = 8 animals.

RESULTS: All loaded groups exhibited superficial chondrocyte death as shown by live/dead imaging. Explants that were articulated against UHMWPE showed macroscopically visible indents and histological evaluation revealed that both UHMWPE groups (hydrophobic and hydrophilic) had greater matrix disruption, surface fibrillation, and chondrocyte clustering compared to CoCr, ceramic, and FSC controls (Fig. 2). Hydroxyproline assays demonstrated a 30–100× increase in collagen wear by UHMWPE groups relative to CoCr and ceramic, and the rate of collagen release followed the same trend **(**$p < 0.0001$) (Fig. 3). Similarly, sGAG quantification by DMMB showed 2.5–3× higher release in UHMWPE groups, with the rate of sGAG release also greatest for UHMWPE and lower for CoCr, ceramic, and FSC **(**$p < 0.0001$) (Fig.3). Metabolic activity was variable and did not show a consistent pattern across groups.

DISCUSSION: These results demonstrate a consistent and statistically significant different tribological response of cartilage to different hemiarthroplasty bearing materials. UHMWPE, hydrophobic and hydrophilic, induced greater matrix disruption and chondrocyte clustering, indicating accelerated cartilage degradation under tribological stress. In contrast, CoCr and ceramic counterfaces preserved cartilage matrix integrity more effectively, with lower rates of collagen and sGAG release. The statistical significancy of these differences underscores the critical role of implant material selection in joint-preserving procedures. Overall, these findings indicate that CoCr and ceramic (ZTA) counterfaces are more effective at maintaining cartilage health under load and provide valuable guidance for material selection in hemiarthroplasty.

SIGNIFICANCE/CLINICAL RELEVANCE: Using and in vitro cartilage wear model, UHMWPE showed accelerated cartilage degeneration compared with CoCr and ZTA, underscoring the importance of material selection and the need to explore alternatives to improve hemiarthroplasty outcomes.

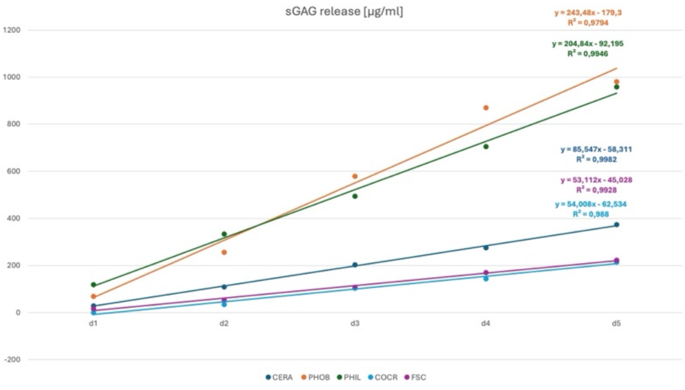

Fig. 1. Cumulative release of sulfated glycosaminoglycans (sGAG) from bovine cartilage explants over 5 days of tribological testing, for 1 animal. Linear regression trendlines with corresponding R^2 values are shown for each material condition.

Fig.2 *Safranin-O Fast Green staining of cartilage surface. Images were taken in the ball articulating area for all four counterfaces and control condition at 10X Magnification.*

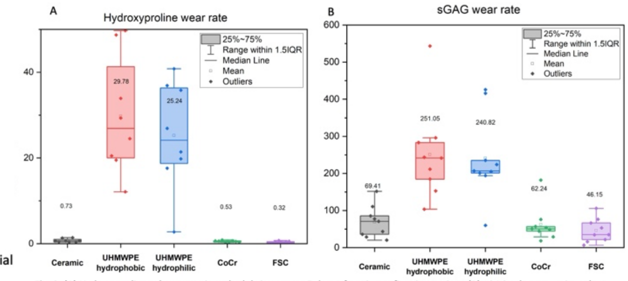

Fig. 3. (A) Hydroxyproline release rate into the lubricant over 5 days of testing at five time points. (B) sGAG release rate into the lubricant over 5 days of testing at five time points.