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Research Paper

Impact of lipid-induced degradation on the mechanical properties of ultra-high molecular weight polyethylene for joint replacements

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ABSTRACT

Gamma or electron beam irradiation of ultra-high molecular weight polyethylene (UHMWPE) used in artificial joints for sterilization and/or crosslinking purposes generates free radicals in the material, which causes long-term oxidative degradation of UHMWPE. Recently, another mechanism for the degradation of UHMWPE by the absorption of lipids during in vivo clinical use was proposed. However, knowledge on lipid-induced degradation is quite limited, compared with that on radical-induced degradation. In this study, lipid-induced degradation was simulated using squalene absorption and subsequent accelerated aging, and its impact on the mechanical properties of UHMWPE was evaluated. The simulated lipid-induced degradation caused an increased elastic modulus and decreased elongation with maximum degradation at the surfaces. These results imply that degradation of UHMWPE may occur during in vivo long-term use, even if free radicals are completely eliminated. Therefore, further investigation is required to clarify the impact of lipid-induced degradation on clinical outcomes, such as the wear and fatigue characteristics of UHMWPE components.

1. Introduction

For many decades, ultra-high molecular weight polyethylene (UHMWPE) has been used as the material for the articulating surfaces of artificial joints. Post-consolidation manufacturing processes of UHMWPE, such as sterilization, irradiation cross-linking, and thermal treatment, have been known to have a significant effect on characteristics such as oxidative stability (Sutula et al., 1995), the mechanical properties (Sutula et al., 1995), and wear resistance (Fisher et al., 1995), and thus the clinical performance. Until 1995, UHMWPE was typically sterilized with gamma irradiation in air (Kurtz et al., 1999). Gamma irradiation has now been known to generate free radicals, which cause long-term oxidative degradation of the polymer (Costa et al., 1998). This radical-induced oxidative degradation reduces the mechanical properties of UHMWPE, which results in cracking and delamination of UHMWPE components (Sutula et al., 1995) and an increase in the wear rate (Fisher et al., 1995). UHMWPE wear debris is phagocytosed by macrophages, which results in the activation of

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cytokine release and subsequent osteolysis (Amstutz et al., 1992). Highly crosslinked UHMWPE was developed to reduce wear and the release of wear debris (Kurtz et al., 1999). The crosslinking of UHMWPE was typically achieved with gamma or electron beam irradiation at a dose of approximately 100 kGy, which is much higher than that used for sterilization. Thermal treatment is thus often conducted to eliminate free radicals generated during irradiation processes. Much research and development conducted by the orthopaedic community on the oxidative degradation of UHMWPE induced by free radicals generated through irradiation processes has led to modern products that are not subject to degradation by radicals, because they are treated with appropriate methods to prevent radical-induced degradation (Kurtz, 2009).

Recent studies have, however, suggested another type of degradation mechanism, where the in vivo environment may affect the long-term clinical performance of UHWMPE. Costa et al. (2001) have reported that lipids in the joint fluid are absorbed into UHMWPE in vivo. Lipids such as squalene and cholesterol esters were identified from retrieved UHMWPE components by hexane extraction. Oral et al. (2012) have simulated lipid-induced degradation using squalene absorption and subsequent accelerated aging. They claimed that UHMWPE was oxidized by squalene absorption and subsequent accelerated aging, based mainly on an increase of the oxidation index (OI) of UHMWPE; however, the effects of lipid-induced degradation on the mechanical properties of UHMWPE were not reported. To the best of our knowledge, there have been no reports regarding the effect of lipid-induced degradation on the mechanical properties of UHMWPE. Therefore, lipid-induced degradation was simulated in the present work using squalene absorption and subsequent accelerated aging, and its impact on the mechanical properties of UHMWPE was evaluated.

2. Materials and methods

Dumbbell-shaped tensile test specimens (JIS K7113-1995 type II; total length: 115 mm; length of narrow section: 33 mm; width of narrow section: 6 mm; thickness: 3 mm) were machined from sheet compression-molded UHMWPE (GUR 1020). Rectangular compression test specimens with dimensions of $4 \times 8 \times 60$ mm were machined from the same material. The compression test specimens were also used for microindentation tests. Specimens for tensile punch tests with dimensions of 6 mm x 6 mm x 0.5 mm were cut from direct compression-molded UHMWPE sheet (0.5 mm thick).

Seven materials, including as-machined (Virgin), were prepared from these specimens, as shown in Fig. 1. G100R was prepared by gamma irradiation at 100 kGy in an inert atmosphere and then remelted at 160 °C for 2 h in vacuum. G100A was prepared by gamma irradiation at 100 kGy in an inert atmosphere, followed by annealing at 110 °C for 168 h in vacuum. SQ^+ was prepared by immersion in squalene (198-09735, Wako Pure Chemical Industries, Osaka, Japan, includes ca. 0.05% (±)-α-tocopherol as a stabilizer) at 80 °C for 14 days. SQ^+AA was prepared by the accelerated aging of SQ^+ at 80 °C for 21 days in air (ASTM F2003-00). SQ^-AA was prepared by immersion in squalene without a stabilizer (H0097, Tokyo Chemical Industry, Tokyo, Japan) at 80 °C for 14 days followed by accelerated aging at 80 °C for 21 days in air. G25AA was used as a representative specimen of radical-induced degradation, prepared by gamma irradiation at 25 kGy in air, followed by accelerated aging at 80 °C for 21 days in air.

Tensile tests were performed by fixing both ends of a tensile test specimen in a universal testing machine (Autograph AG-20kNG, Shimadzu, Kyoto, Japan) using wedge-shaped fixation jigs. The load cell capacity was 20 kN and the displacement rate was 50 mm/min. A non-contact digital video extensometer (TRViewX, Shimadzu, Kyoto, Japan) was used to measure the elongation. Yield stress, fracture stress and elongation at break were calculated from the obtained stress–strain curves. Five specimens of each material were tested.

Tensile punch tests were performed using a method that we developed in a previous study (Sakoda and Matsuoka, 2011), the experimental setup of which is shown in Fig. 2.

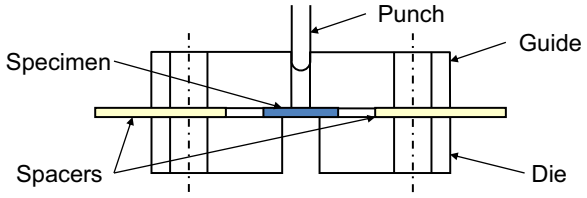

Fig. 2 – Schematic diagram of the tensile punch test setup used in this study.

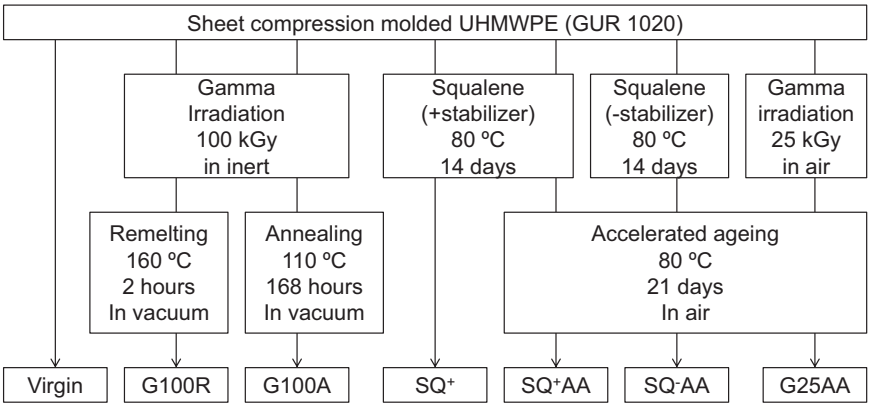

Fig. 1 – Post-consolidation processes to prepare the materials used in this study.