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Wear of Retrieved UHMWPE Hip Liners

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After the gamma-irradiation sterilization, the most widely used orthopaedic grade polymer bearing liner material for the total joint replacement, ultra-high molecular weight polyethylene (UHMWPE), degrades through the progressive in vivo oxidation. The oxidative degradation makes UHMWPE brittle and leads to reduction of its mechanical properties. In this study, the effect of the in vivo post-irradiation ageing time on the wear of UHMWPE was investigated. Twelve retrieved polyethylene hip liners implanted for 3-16 years and then stored in the air for 1.5-8 years were used. Two types of the pin-on-disk wear testing were conducted. The uni-directional repeat pass rotating and the linear reciprocating wear testing were done with stainless steel disks against stationary polyethylene pins under 4MPa at 1Hz with bovine serum lubrication. Wear of the retrieved polyethylene hip liners does not have significant correlation with the *in vivo* or total ageing time. The linear reciprocal sliding motion generated a more pronounced wear than the uni-directional repeat pass sliding motion. This indicates that the kinematic motion significantly affects the wear of aged UHMWPE, having a brittle, white band region.

Key Words: UHMWPE, wear, ageing, brittleness, kinematic motion, retrieved hip liner

INTRODUCTION

Sir Charnley adopted a combination of the metal head and polymer liner for the total hip joint arthroplasty in the early 1960's. Since then, Polytetrafluoroethylene (PTFE), low density polyethylene (LDPE), high density polyethylene (HDPE), carbon-reinforced polyethylene, ultrahigh molecular weight polyethylene (UHMWPE), Ti-alloy, and alumina ceramics, etc., have been used as the bearing liner materials. Stainless steel, Ti-alloy, CoCr-alloy, alumina and zirconia ceramics have been used as the femoral head materials. Recently, ceramic heads have become popular in European and Asian countries. For special cases, like young patients, metal-metal or ceramic-ceramic hip joint pairs have been tried. So far, however, UHMWPE bearing liner is a world-wide standard in the total hip joint replacements.

Though the total joint replacement has attained a spectacular success in patients with the end-stage joint problems, the polyethylene wear and the malign response of the periprosthetic bone tissue due to the wear debris limit the longevity of the total joint arthroplasty. Submicron-sized wear particles from the UHMWPE component have been implicated as a major contributor to the bone resorption and subsequent aseptic loosening of the total joint components.[1-3] Therefore, many efforts have been made to prevent or reduce the wear particle generation from UHMWPE components. Tribological issues concerning the design of the components, material pairs, mechanisms of wear, surface roughness of the femoral head, abrasion by 3rd body hard particles, such as bone cement, metal debris from modular neck joint and porous coating, and bone chip, etc., have been extensively studied.[4-8]

Additional issues of molecular structural changes

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due to the oxidation and progressive ageing in UHMWPE during and after the gamma-irradiation sterilization and subsequent degradation in its mechanical properties, including the wear resistance of UHMWPE, have also been profoundly analyzed.[9-13] High-energy photons of gamma-rays during the sterilization process break the molecular chains in UHMWPE and generate free radicals. Some of the free radicals react with the oxygen molecules diffused from the environment during the irradiation, which initiates oxidation in UHMWPE. The last of the free radicals trapped inside are active for a long time and continue to oxidise. This process results in thickening of the oxidized surface layer as the ageing time increases. The gamma-irradiation not only causes oxidation, but also increases the level of crosslinking in UHMWPE. The shortened molecular chains have more chances to be physically entangled and to recombine with the same or neighbouring chains, resulting in chemical crosslinking. An increase of the crosslinking level in UHMWPE improves its wear resistance.[14-16] However, this crosslinking increased by the gamma-irradiation dramatically decreases after 5 - 6 years of the post-irradiation ageing time.[13,17,18]

These progressive changes in the molecular structure of UHMWPE during ageing cause changes in its mechanical properties. Highly oxidized-subsurface layer, called the white band, shows a significant decrease in the elongation and ultimate tensile strength of UHMWPE.[19] Previous wear studies on the shelf-aged UHMWPE showed that the oxidation progressed with time and decreased the level of crosslinking. The process was accompanied by the appearance of white bands and brittle cracking, and, in turn, this oxidative degradation reduced the wear resistance with ageing.[20,21] Therefore, recently new processing and sterilization methods for prevention of the oxidation and improvement of the level of crosslinking in UHMWPE have been developed.[22,23]

For the retrieved acetabular liners, another study showed no detrimental effect of the ageing time on the wear performance of UHMWPE.[24] In case with the *in vivo* ageing, additional effects of the *in vivo* mechanical load are involved in the changes of the molecular structure. In this study, by using the post-irradiation of the *in vivo* aged (retrieved) UHMWPE hip acetabular liners, the effect of the post-irradiation ageing time on the wear of UHMWPE was investigated. Furthermore, the effect of the kinematic motion on the wear of the aged brittle UHMWPE was also studied.

MATERIALS AND METHODS

Specimens

Twelve retrieved polyethylene hip acetabular liners, which were gamma-irradiated, aged *in vivo* for 3 - 16 years and then stored in the air for 1.5- 8 years, were used. Table 1 presents the ageing

Table 1. Aging Time of Retrieved Liners before the Wear Tests

Liner	*In vivo*	Shelf	Total
#1	3yrs 1mo	4yrs 3mos	7yrs 4mos
#2	6yrs 8mos	4yrs 1mo	10yrs 9mos
#3	4yrs 4mos	6yrs 8mos	11yrs
#4	7yrs 2mos	4yrs 8mos	11yrs 10mos
#5	10yrs 2mos	2yrs 1mo	12yrs 3mos
#6	11yrs	2yrs 1mo	13yrs 1mo
#7	13yrs	1yr 7mos	14yrs 7mos
#8	12yrs 11mos	1yr 9mos	14yrs 8mos
#9	12yrs 9mos	2yrs 1mo	14yrs 10mo
#10	9yrs 9mos	8yrs 4mos	18yrs 1mo
#11	16yrs	2yrs 1mo	18yrs 1mo
#12	12yrs 6mos	7yrs 9mo	20yrs 3mo

time of each liner specimen. All the liners were cored by a hollow punch (10-mm diameter) and machined to cylindrical pin specimens having a right angle. Three pin specimens were prepared from each liner. Two pins were used in two different kinematic motion wear tests, respectively, and one pin was used for the soak control test. When all the aged liners were cored, the macro-scale cracks near the punched holes and subsurface white bands were visually observed on the six liners. This brittle layer was almost removed during the machining process. Each pin was tested against orthopaedic grade stainless steel flat disks. Six disk specimens were highly polished (R_a=0.02 μm) with silicon carbide abrasive papers and alumina powder.

Wear testing

Two types of pin-on-disk wear tests were conducted under the uni-directional repeat pass rotational motion and the linear reciprocal motion (Fig. 1). A nominal contact pressure of 4MPa was applied to each pair of the contacting specimens by a lever arrangement and dead weights. The disk moved along a distance of 63 mm per each cycle at 1Hz. Both the uni-directional repeat pass rotational and the linear reciprocal motions provided an equal sliding distance per each cycle. Bovine serum diluted with 1% sodium azide solution at the volume ratio of 2 : 1 (serum : solution) was used as a lubricant at room temperature.

All the tests were interrupted after every 100 thousands cycles. The UHMWPE pin was cleaned with alcohol and deionized water by an ultrasonic cleaner, dried with a cloth, and weighed with a microbalance (sensitivity of 0.01 mg). The wear testing continued until the total of 500 thousand cycles of sliding for all the pin specimens was done. The wear amount of each UHMWPE pin specimen was determined by the weight loss, which was corrected for the weight gain that was obtained from the soak control test.

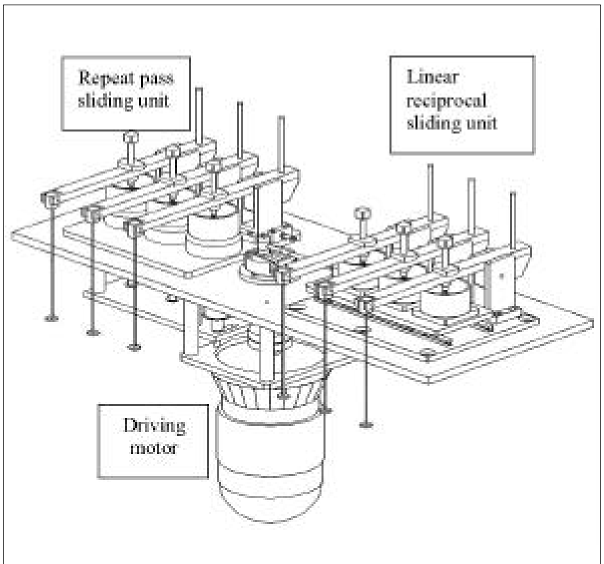

Fig. 1. Schematic diagrams of the pin-on-disk wear testing apparatus having three repeat pass sliding stations and three liner reciprocal sliding stations.

RESULTS

White band and brittleness

When all the retrieved hip acetabular liners were cored by the hollow punch, six (liner #1, #2, #4, #5, #6, #11) of them were so brittle that many macro-scale cracks formed near the edge of the punched hole. These brittle liners had white bands on the subsurface, and the 1 - 2 mm thick surface layer from the articulated concave surface of each punched pins were easily separated by brittle fracture and fragmentation (Fig. 2). No cracks and white bands were visually observed in the other six liners (#3, #7, #8, #9, #10, #12). The degree of brittleness of each liner failed to correlate with the ageing (*in vivo* or total) time.

Wear variations

The variations of the wear were plotted as a function of the sliding cycle for both the repeat pass sliding and the linear reciprocal sliding motions (Fig. 3). For all the liners, the wear increased linearly as the sliding cycle increased. The wear rates (the slopes of the linear curve fit) and linear regressions for all the cases are presented in Table 2. The wear rates under the repeat pass sliding motion were much lower than those under the linear reciprocal sliding motion for all the liners.

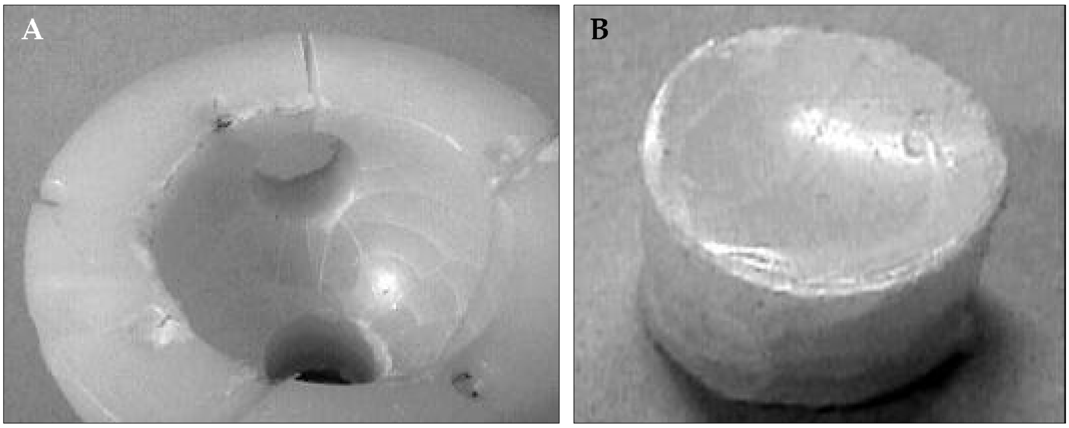

Fig. 2. Photographs showing the brittle cracks (A) near the punched hole of liner #1 and (B) on the pin from liner #11.

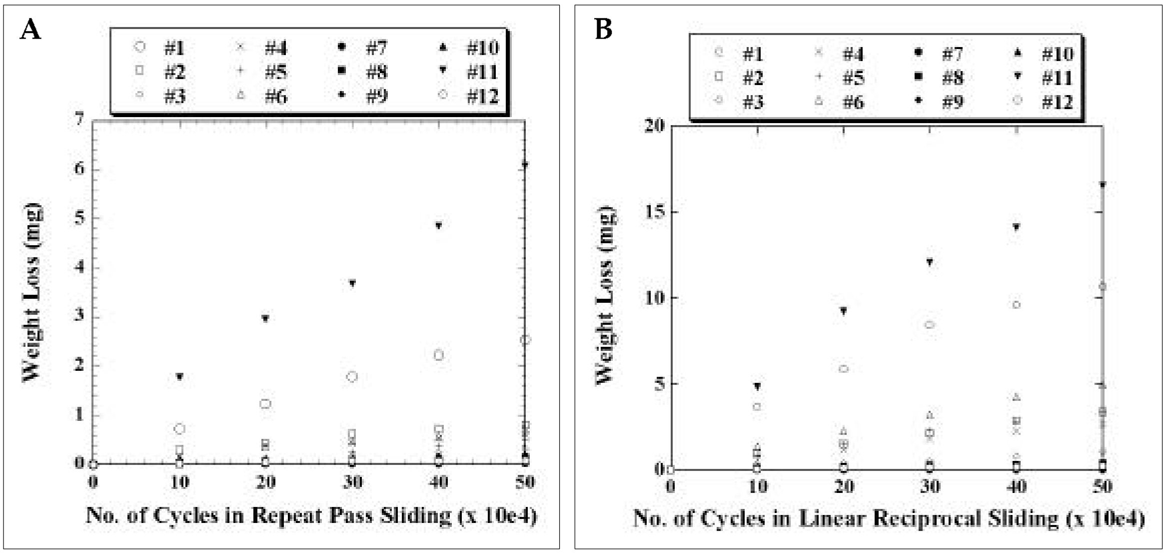

Fig.3. Wear changes of retrieved liners as a function of the number of cycles in both (A) repeat pass sliding and (B) linear reciprocal sliding motions.

Effects of ageing time and kinematic motion

The total wear amounts of all the aged UHMWPE quantum after 500 thousand cycles were plotted in the order of the total ageing time in Fig. 4. Liner #1 and #11 showed a very high wear, while liner #10, #8, #9, and #12 showed a low wear and liner #7 did not show any wear. The wear of the six liners, having brittle macro-cracks when they were punched and with white bands, were much higher than the wear of the other six liners having no cracks and white bands. No correlation between the wear and the total ageing time was noted. The total wear amount of all the aged UHMWPE pins were plotted in the order of the *in vivo* ageing time again in Fig. 5. There was no correlation between the wear and the *in vivo* ageing time for all the tested liners.

The wear under the linear reciprocal motion was higher than the wear under the uni-directional repeat pass rotational motion for all the liners. The difference in the wear under these different kinematic motions become larger in the group of the liners having brittle cracks and white bands than for the other group of liners having no cracks.

Table 2. Wear Rates of Retrieved Liners for Each Kinematic Motion

Liner	Repeat Pass SlidingLinear		Reciprocal Sliding	
	Wear Rate ($\times 10^{-4}$)	Regression	Wear Rate ($\times 10^{-4}$)	Regression
#1	0.0507	0.99	0.2103	0.98
#2	0.0158	0.98	0.0658	0.99
#3	0.0063	0.99	0.0205	0.99
#4	0.0121	0.97	0.0544	0.99
#5	0.0106	0.99	0.0667	0.99
#6	0.0142	0.99	0.0989	0.99
#7	0.0004	0.86	0.0006	0.98
#8	0.0027	0.98	0.0073	0.98
#9	0.0037	0.98	0.0056	0.99
#10	0.0029	0.99	0.0036	0.98
#11	0.1153	0.99	0.3238	0.98
#12	0.0017	0.97	0.0045	0.98

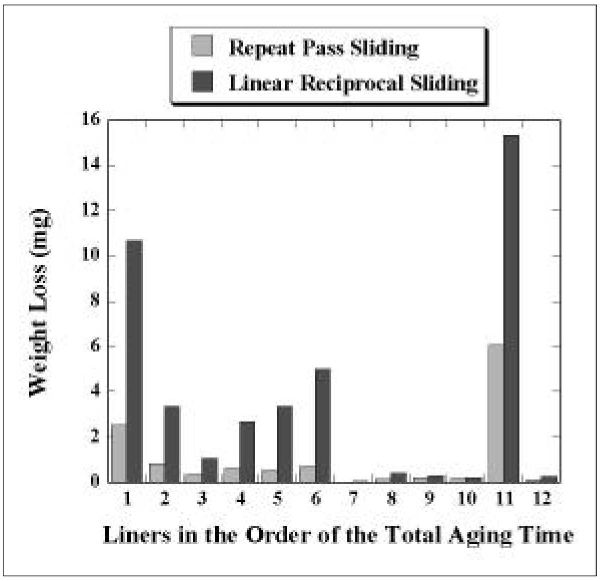

Fig. 4. Wear of retrieved liners under both the kinematic motions in the order of the total aging time.

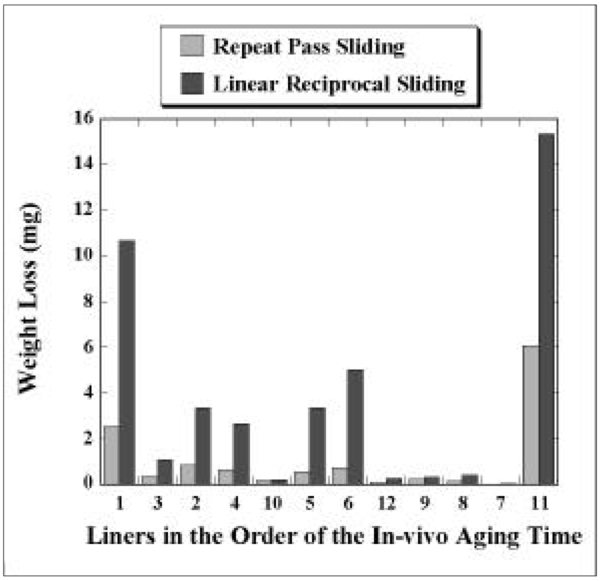

Fig. 5. Wear of retrieved liners under both the kinematic motions in the order of the *in vivo* aging time.

DISCUSSION

Most of the liners having a white band region were so brittle that they cracked on the macro-scale, and their wear rates were high even with the ageing time of the tested liners being relatively short, while liners having no white bands were not brittle, and their wear rates were low with relatively a longer ageing time. Therefore, white bands and brittle cracking seem to contribute to the wear of polyethylene. However, it does not mean that the longer the aging time is, the more white bands are noted. According to another study,[19] aged retrieved liners did not always have white band. The white band is a highly oxidized subsurface layer with low mechanical properties. In the previous study,[21] for the shelf-aged liners, generally the degree of oxidation increased, the degree of crosslinking decreased, and the wear increased as the ageing time increased. Most shelf-aged liners with the ageing time above 5 years, except one liner, which was fabricated with a different resin, had white bands and showed a very high wear. In the present study, however, the wear of the retrieved liners showed no correlation with the total or the *in vivo* ageing time. The wear depends on the brittleness of UHMWPE rather than on the ageing time. The non-correlation between the wear of the retrieved liners and the ageing time is consistent with other results.[24]

Why there are different wear results between the shelf-aged and the *in vivo* aged polyethylene liners? The major differences in the exogenous factors are that the dynamic mechanical load is put on and the wear occurs in the synovial fluid. There is no evidence that the emergence of the white band is related to the history of the mechanical load *in vivo* and to the synovial fluid environment. The formation of the white band may depend on the resin type, processing method, procedure in sterilization, etc. Unfortunately, there is no information about what kind of resin was used, what kind of additive was used, how to manufacture the polyethylene rod or sheet and the final product, and what are the dose, temperature, and environment of the gamma-irradiation process for all the tested retrieved liners. The total aging time may be also inaccurate because there is no information about when these liners were gamma irradiated and how long was the pre-implantation shelf ageing time after the sterilization before the implantation for each of the retrieved liners. In any case, however, it is clear that brittle polyethylene liners having white bands have a low wear resistance. New polyethylene liners, which were manufactured, sterilized, and stored for a short period (several months), should be implanted to patients.

For all the tested liners, the linear reciprocal motion is associated with a higher wear than the uni-directional repeat pass rotational motion. Under the conditions of the linear reciprocal motion, the surface traction changes to the opposite direction every half cycle, while it does only in a limited range, depending on the radius of the wear track, of the sliding direction at any moment under the conditions of the uni-directional repeat pass rotational motion. This difference between the two kinematic motions is responsible for these totally different stress states in the UHMWPE pin specimen. Frequent changes in the direction of the contact stress may play a crucial role in the fatigue wear. In addition, at the interface between the brittle white band and relatively ductile regions the subsurface cracking may be initiated by the stain mismatch. This subsurface crack will propagate under the cyclic stress applied during the *in vivo* service and cause a delamination, especially, in the knee.[25] In the present study, the liners having brittle cracks and a highly-oxidized white band region wore 2.5 - 7.0 times more under the linear reciprocal motion than under the uni-directional repeat pass rotational motion. On the other hand, the liners having no cracks wore 1.2-3.0 times more under the linear reciprocal motion than under the uni-directional repeat pass rotational motion. For the brittle liners having a high degree of oxidation and subsequent low level of crosslinking, the more directional changes in the contact stress will lead to more readily crack or fragmentation formation; thus, the wear increases significantly.

In this study, from the pin-on-disk wear tests, the wear of retrieved (aged) UHMWPE acetabular liners does not have any correlation with the total or the *in vivo* ageing time. From the viewpoint of the kinematic motion effect, the linear reciprocal motion produces a remarkable increase of the wear in the aged liners having brittle cracks and white bands. To the extent that the mechanical brittleness predominantly affects the wear of polyethylene, the oxidative degradation and white band formation should be prevented or retarded in UHMWPE for the total joint replacement.

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