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Wear mode and wear mechanism of retrieved acetabular cups

Accepted: 12 May 2003 / Published online: 21 June 2003
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Abstract Nineteen ultra-high-molecular-weighted polyethylene (UHMWPE) cups were retrieved at revision surgery. The implant period was on average 9.9 (0.25–20.7) years. The cups were classified into the high-wear group (wear rate above 140 mm³/year), intermediate-wear group (wear rate 80–140 mm³/year) and low-wear group (wear rate below 80 mm³/year). The wear rate was measured by a fluid displacement method. The cups were studied using scanning electron microscopy. Ripples mainly appeared on the cups in the low-wear group, and nodules and fibrils mainly appeared in the high-wear group. Folding was observed in all cups, but folding with numerous fibrils was conspicuous in the high-wear group. The cup retrieved at 3 months already exhibited folding. From these results, the wear response appeared to be a three-step process: (1) foldings are generated, (2) ripples are formed on the surface, and (3) fibrils are produced from the surface and delaminated, leading to the formation of wear debris.

Résumé Dix-neuf cupules de polyéthylène (UHMWPE) ont été retirées au cours de chirurgie de révision. La durée d'implantation était en moyenne de 9.9 (0.25–20.7) années. Les cupules ont été classées dans le groupe d'usure importante (au-dessus de 140 mm³/an), le groupe d'usure intermédiaire (80 à 140 mm³/an) ou le groupe

de faible usure (au-dessous 80 mm³/an). Le taux d'usure a été mesuré par une méthode de déplacement de fluide. Les cupules ont été étudiées par microscopie électronique. Des sillons sont apparus principalement sur les cupules du groupe d'usure faible, des nodules et des fibrilles sont apparus surtout dans le groupe d'usure importante. Un plissement a été observé sur toutes les cupules, mais un plissement avec de nombreuses fibrilles était visible dans le groupe d'usure importante. La cupule retirée à trois mois avait déjà ce plissement. De ces résultats, l'usure paraît être un processus en trois temps: (1) les plissements se produisent, (2) les sillons sont formés sur la surface, et (3) les fibrilles sont produites à partir de la surface et délamainées, menant à la formation des débris d'usure.

Introduction

Recently, wear debris of the ultra-high-molecular-weighted polyethylene (UHMWPE) cup as a component of the articular surfaces of joint prostheses has been identified as a serious problem as one of the causes of osteolysis around, and loosening of, the prosthesis [1, 4, 11]. In order to reduce polyethylene (PE) wear, various combinations of the materials composing the articular surfaces have been studied, and many experiments have also been carried out to enhance the wear resistance of UHMWPE [7, 8, 9, 12, 14].

To improve the quality of the cup, it is important to understand the mechanism of the wear mode on the actual PE surface. Especially, comparing the wear modes between the PE cups in the low-wear condition and in the high-wear condition and understanding those differences can contribute to the development of PE with excellent wear resistance. Several authors reported on “adhesive”, “abrasive”, and “fatigue” wear, but various terminologies have been used to describe the micro-mode changes on the PE surface with the progress of PE wear, and many factors of the mechanisms are unknown [3, 6, 10, 13]. In addition, there seems to be no

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Fig. 1 **a** Polyethylene (PE) cup in the high-wear group showing a nodular surface and many long fibrils. **b** PE cup in the high-wear group showing extensive foldings accompanied with fibrils circumferentially. **c** Many scratches were observed on the cup in the high-wear group. **d** Micro-delaminations observed on the cup in the high-wear group

report on the changes on the PE surface with the actual progress of wear. Therefore, we used scanning electron microscopy (SEM) to analyse the condition of articular surfaces of the retrieved UHMWPE cups with different wear rates and attempted to determine wear mechanisms.

Materials and methods

We examined 19 UHMWPE cups that had been retrieved at revision surgery from December 1998 to May 2001. Patient age ranged from 36 to 76 (average 57.6) years. Four cases were men and 15 were women. The periods from initial surgery to revision surgery ranged from 3 months to 20.7 years (average 9.9 years). Causes of revision were loosening in 16 cases, infection in two and repetitive dislocation in one. The retrieved UHMWPE cups consisted of 17 made of GUR4150 resin (Mallory-head acetabular cup system, Biomet Inc., Warsaw, IN, USA) and two of RCH 1000 resin (Acetabular cups, Howmedica Inc., Rutherford, NJ, USA), which were all irradiated by 2.5 MGy of gamma ray in air. The used femoral heads were seven titanium, 11 CoCr and one Zirconia. At surgery, cemented fixation was used in eight cases and cementless fixation in 11.

The amount of wear of these PE cups was measured using the oil drop method designed by Biggs et al. [2, 5]. In this method, we used a Pasteur pipette containing 20.77 mm³ per drop, and dropped vegetable oil in the gap between the standard-positioned femoral head and the PE cup. We then calculated the total amount of PE wear from the number of drops. The average wear rate was calculated from the total amount of PE wear and the implant period until revision surgery. The cups were classified into the high-wear group (wear rate above 140 mm³/year), intermediate-wear group (wear rate 80–40 mm³/year) and the low-wear group (wear rate below 80mm³/year). We observed and compared three groups using the low-voltage SEM (Philip XL 30 FEG) regarding fibrils (fibrous forms stretching from the PE surface), nodules (knotty forms apparently swelling from the PE surface), ripples (changes resembling repetitive small waves on the PE surface), folding (conditions in which peripheral PE layers fold on the original surface), delaminations (layered detachment) and scratches (various lengths of groove-like linear scratched cut). We also observed and compared the articular surfaces of the control soak cups, which had been obtained from another study using a hip simulator (Shore Western Manufacturing Inc., Monrovia, CA, USA) and that had been exposed to 8-million-cycle loading without oscillating.

Results

The total amounts of PE wear of the 19 cups ranged from 21 mm³ to 2,151.6 mm³ (mean±SD: 1043.9±571.3 mm³), and the average amounts of annual wear ranged from 17.5 mm³/year to 167.9 mm³/year (mean±SD: 106.2±50.8 mm³/year). In 19 cups, four were classified into the high-wear group, ten into the intermediate-wear group and five into the low-wear group. We observed cups of

Fig. 2 **a** Polyethylene (PE) cup in the intermediate-wear group showing fewer fibrils and foldings accompanied with fibrils than in the high-wear group. **b** PE cup in the intermediate-wear group showing ripples at several sites. **c** PE cup retrieved 3 months after surgery. Although no ripples are seen, foldings are already observed

each group using an SEM. In the high-wear group, machine marks disappeared extensively around the loaded area and there were remarkable typical nodular surfaces, many 2–5µm long fibrils (Fig. 1a), as well as foldings (Fig. 1b) accompanied with numerous fibrils. Long multi-directional scratches (Fig. 1c) were also observed extensively. Delaminations (Fig. 1d) were seen in several sites, but ripples were rarely observed.

In the intermediate-wear group, machine marks disappeared on the loaded area again, and nodules, fibrils and foldings with fibrils were observed, but not as many as seen in the high-wear group (Fig. 2a). Ripples were seen in several sites (Fig. 2b). Scratches and delaminations were observed as frequently as in the high-wear group. However, on the PE cup in the intermediate-wear group, retrieved at 3 months, foldings were already seen but no ripple was observed (Fig. 2c). No delaminations were found.

In the low-wear group, machine marks disappeared as well. Many foldings were observed, but no or very few fibrils were observed (Fig. 3a), and many ripples were seen extensively (Fig. 3b). Scratches and delaminations were observed, as in the other groups.

Fig. 3 **a** Polyethylene (PE) cup in the low-wear group showing extensive foldings, but few fibrils. **b** PE cup in the low-wear group showing extensive ripples

Fig. 4 Control soak cup. Although no oscillating had been applied, foldings are observed

On the control soak cups, despite no oscillating being applied, foldings were already seen (Fig. 4). No formation of ripples or fibrils was observed.

Discussion

In 1973, Walker et al. [13] described ripples, surface fibrils and cracking on the worn UHMWPE surfaces. Rostoker et al. [10] observed erosion of the machine marks on both the simulator cups and the retrieval cups, and also described folds as “deformed into projecting and overlapping lamellae.” Dowling et al. [3] observed “parallel ripple(s)” on the worn area of the PE cups at 8 years or more after surgery. Various terminologies have been used to describe wear modes and associated with wear mechanisms, such as “adhesive,” “abrasive,” and “fatigue” types, but actually the mechanisms have not been clearly defined as yet. McKellop et al. [6] also mentioned in their simulator study that fibrils were generated as a result of abrasion, adhesion or fatigue.

From the results of our study, we found that there were many ripples but few fibrils on PE cups that had been implanted for a long time and had a very large total amount of wear debris but had been slowly worn. However, there were numerous fibrils and rare ripples on the PE cup that had been implanted for a shorter time and had a lower total amount of wear debris but had been rapidly worn. Therefore, we assume that fibrils are likely to be formed under circumstances in which the cup is rapidly worn and is susceptible to abrasive force. Ripples are generated under the circumstances in which the PE cup is slowly worn, and they disappear under rapid wear conditions, so they may be associated with adhesive force. In addition, an interesting point is that foldings are already seen on cups without oscillation, and this may prove that at least foldings can be generated regardless of the abrasive force.

Fig. 5 Wear mechanisms of the UHMWPE acetabular cup

It is very difficult to discuss the specific process of PE wear with time using retrieved cups. However, as mentioned before, there are different wear modes between PE cups that clinically have been worn rapidly and slowly. We presume the PE wear process to be three steps: (1) foldings are generated first, (2) ripples are formed, and (3) when the PE cup is exposed to more severe wear condition, ripples decrease and fibrils increase.

We assume that, firstly, foldings are generated by the loading force on the PE surface; secondly, ripples are formed by the sequential loading-shear force; and thirdly, fibrils are produced from the surface and delaminated, leading to the formation of wear debris (Fig. 5). In a previous study by our group [15], we reported that on the cross-linked UHMWPE cup, the amount of PE wear decreased as the radiation dose increased. On the non-cross-linked UHMWPE cup, the articular surface had numerous fibrils, but as the radiation dose increased, fibrils became shorter and fewer in number, and the shapes of wear debris were all similar. This report is consistent with the results of the present study in which, as the radiation dose increased, PE wear decreased, and in the low-wear condition, fibrils decreased. This may mean that the above-mentioned wear process was restrained by cross-linking.

However, wear modes in identical materials as used in our study may differ depending on the wear rate, regardless of the total amount of PE wear. Therefore, it is important not only to develop wear-resistant PE, but also to create the circumstances of low wear, as well as to deal with the problems of the femoral head and circumferential factors. Future developments are expected in this field.

Acknowledgement The authors are indebted to Professor J. Patrick Barron of the International Medical Communications Center of Tokyo Medical University for his review of this manuscript.

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