Oxidation and Wear of 100-Mrad Cross-linked Polyethylene Shelf-aged for 30 Years

Hironobu Oonishi MD, PhD, Sok Chol Kim MD,
Hiroyuki Oonishi MD, Masayuki Kyomoto MSc,
Shingo Masuda MSc

© The Association of Bone and Joint Surgeons 2008

Abstract Some previous studies suggest that aging influences wear and oxidatively degraded nonsterilized ultra-high-molecular-weight polyethylene (UHMWPE) exhibits decreased wear resistance. We therefore asked whether shelf-aging storage conditions influenced degradation and wear resistance of gamma-irradiated UHMWPE. We examined oxidation and wear of 100-Mrad gamma-irradiated UHMWPE (100-Mrad polyethylene) cups shelf-aged for 30 years without ($n = 2$) or with ($n = 2$) packages. The oxidation index of the unpackaged 100-Mrad polyethylene surface (4) was higher than that of the packaged one (2.7). The packaged 100-Mrad polyethylene cup exhibited a high wear resistance with a steady wear rate of $0.5 \text{ mg}/10^6$ cycles. In contrast, the unpackaged 100-Mrad polyethylene exhibited an extremely high initial wear rate of $187.9 \text{ mg}/10^6$ cycles over the first 0.25×10^6 cycles with a subsequently reduced wear rate of $5 \text{ mg}/10^6$ cycles after 5×10^6 cycles. Packaging over long periods

inhibits surface oxidation and maintains the wear resistance of gamma-irradiated UHMWPE cups.

Introduction

Gamma irradiation at a dose of 25 to 45 kGy in air is typically used for sterilizing the ultra-high-molecular-weight polyethylene (UHMWPE) components of artificial joints. Several investigators have reported the wear resistance of gamma-sterilized UHMWPE is better than that of ethylene-oxide-sterilized UHMWPE [5, 8, 13, 14, 25]. On the other hand, many previous reports have indicated gamma-sterilized UHMWPE undergoes degradation [2, 11, 26]. In 2000, McKellop et al. [16] prepared UHMWPE cups that were subjected to accelerated aging by oxidation (80°C heat treatment for 14 or 30 days) and evaluated them with a hip simulator. They reported before aging, gamma-sterilized PE exhibited a lower wear rate than nonsterilized PE; however, after aging, gamma-sterilized PE exhibited both stronger oxidative degradation and a higher wear rate than nonsterilized PE. These findings suggest aging influences wear and oxidatively degraded UHMWPE exhibits decreased wear resistance. Subsequently, major orthopaedic manufacturers began using gamma irradiation in an inert gas, ethylene oxide gas, or gas plasma for sterilization because it was evident that gamma sterilization in air caused the oxidative degradation of the chemical and mechanical properties of UHMWPE during long-term shelf storage.

In 1966, Awatani and Hashimoto [1] reported the beneficial effects of irradiating the surface layer of PE with high-dose irradiation (much higher than used for sterilization). In 1970, Shikita and Oonishi collaborated with Igaki to develop cross-linked PE that was gamma-irradiated at a

Each author certifies that he or she has no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.

Each author certifies that his or her institution either has waived or does not require approval for the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

H. Oonishi, S. C. Kim, H. Oonishi
H. Oonishi Memorial Joint Replacement Institute, Tominaga
Hospital, Osaka, Japan

M. Kyomoto, S. Masuda (✉)
Research Division, Japan Medical Materials Corporation,
Uemura Nissei Bldg 9F 3-3-31 Miyahara, Yodogawa-ku, Osaka,
Japan
e-mail: masudas@jmmc.jp

dose of 1000 kGy (100 Mrad), with the anticipation of improving wear and creep resistance [22]. A limited number of PE cups prepared by gamma irradiation at approximately 100 Mrad (henceforth called 100-Mrad PE) were first implanted in 1971, and they were subsequently marketed in 1973 [17, 18]. These cups were withdrawn from the market in 1978 owing to the bankruptcy of the company providing the special irradiation treatment. However, over the last 30 years, excellent clinical results have been observed with 100-Mrad PE [9, 18, 27]. Several studies suggest the linear wear rate in vivo of acetabular cups made from conventional PE (gamma-sterilized in air or inert gas) is as high as 0.1 to 0.2 mm per year [6, 7]. In contrast, the wear rate of 100-Mrad PE measured from radiographs has been reported as 0.04 ± 0.02 mm per year (and as 0.32 mm per year of conventional PE in the same condition) [17, 20]. Moreover, the wear in retrieved 100-Mrad PE cups was just 0.003 to 0.010 mm per year, 3%–10% that of conventional PE [12].

However, oxidative chain scission and degradation are induced in gamma-sterilized UHMWPE. The reported wear values for gamma-irradiated UHMWPE depend on the aging conditions such as accelerated aging condition (eg, stored in a heat chamber), shelf life for stored implants, and in vivo aging [2, 3, 11, 26].

We asked whether shelf-aging storage conditions (unpacked versus packaged) influenced degradation (oxidation index, free radicals, weight loss) and wear resistance of gamma-irradiated UHMWPE.

Materials and Methods

We investigated the wear and oxidation of four 100-Mrad PE cups that had been shelf-aged without ($n = 2$) or with ($n = 2$) packages for 30 years (1973–2003). One cup of each was used to determine oxidation and free radicals and one was used to determine wear in a simulator. The four 100-Mrad aged PE cups were manufactured by Mizuho Medical Instruments Ltd (Tokyo, Japan) in the 1970s. They were produced by the gamma irradiation of compression-molded UHMWPE (GUR412 resin; Hoechst AG, Frankfurt, Germany) at 100 Mrad in air; the UHMWPE had been machined into the final product shape and was packaged in a PE bag containing air. After irradiation, they remained in stock on the shelf in the hospital (Kokuritsu Osaka Minami Hospital) at room temperature and were either packaged in air-containing triple PE packages (packaged 100-Mrad PE, $n = 2$) or unpackaged (unpackaged 100-Mrad PE, $n = 2$) for approximately 30 years in conditions of natural aging. Although the shielding of the packaged 100-Mrad PE from oxygen was not perfect, the triple PE packaging was believed to prevent the inflow of new air.

For the accelerated aging test, 24 new 100-Mrad PE cups were prepared. The 100-Mrad PE cups were remanufactured by Kyocera Corp (Kyoto, Japan) using exactly the same manufacturing method that was used by Mizuho Medical Instruments Ltd. Twenty-four additional new 100-Mrad PE cups were subjected to accelerated aging conditions according to the ASTM F2003 standard, ie, 80° C in air or in saline for a maximum of 1 year, and the extent of oxidation was estimated as will be described.

The oxidation indices of the 100-Mrad PE cups after the hip simulator test and accelerated aging test were measured by microscopic Fourier transform infrared spectroscopic (FTIR) analysis according to the ASTM F2101 standard. These specimens were tested over the range of 800 to 2000 cm^{-1} using a microscopic FTIR spectrophotometer (Spectrum BX; PerkinElmer Inc, Wellesley, MA) at a resolution of 4 cm^{-1} for 100 scans.

The concentration of residual free radicals in the 100-Mrad PE cups was determined by the electron spin resonance (ESR) technique. The measurements were carried out on an ESR spectrometer (JES-FE2XG; JEOL Ltd, Tokyo, Japan) operating at 9.3 GHz in a double-resonance cavity. The external field was modulated at 100 kHz to detect the first-order derivative of the absorption line. The relative concentration of defects in each grain was calculated by the double numerical integration of the observed absorption-derivative peaks relative to the signal of a control sample (4-hydroxy-2,2,6,6-tetramethyl-4-piperidinol-1-oxyl). Three replicate measurements were performed on each sample, and the average values were taken as the residual free-radical concentration. The initial concentration of residual free radicals was measured using the 100-Mrad PE remanufactured by Kyocera Corp.

The wear test on one unpackaged and one packaged 100-Mrad PE cup was performed using a hip simulator (Advanced Mechanical Technology, Inc, Watertown, MA). The acetabular component was tested using a 36-mm alumina ceramic femoral head (Bioceram; Kyocera Corp). A mixture of 30% bovine serum, 20 mM/L ethylenediaminetetraacetic acid, and 0.2% sodium azide was used as a lubricant. A load simulating a physiologic loading curve with a 1.5-kN peak load was applied with a frequency of 1 Hz. To compensate for the effects of water absorption during the test, we additionally used “load-soak controls” of packaged and unpackaged ($n = 1$ in both cases) 100-Mrad PE. The linear wear was determined at each period.

The morphology (equivalent circle diameter [ECD] and aspect ratio) of wear particles from the simulator test was quantified by scanning electron microscopy according to the ASTM F1877–98 standard. The wear particles were isolated from the bovine serum used for lubrication in the hip simulator test. The isolation and observation of wear particles from the various test intervals were each repeated five times and the mean values were calculated.

The data on the oxidation index [13], concentration of residual free radicals [21], and morphology of wear particles [12] in the retrieved 100-Mrad PE cups ($n = 2$) that were clinically used for 25 to 27 years were referenced from previous studies to compare the results of shelf-aged 100-Mrad PE cups. Furthermore, the data on the oxidation index in the retrieved conventional PE cups ($n = 17$) that were clinically used for 3 to 27 years were referenced from a previous study [13].

For the data of oxidation index of shelf-aged 100-Mrad PE cups, the Student's *t*-test was used to ascertain the differences in the packaged and unpackaged condition and for differences in the wear particles from the simulator test. We used Microsoft Office Excel 2003 (Microsoft Co. Redmond, WA) to determine all statistical differences.

Results

In the two load-soak samples the oxidation index of the unpackaged 100-Mrad PE surface (4) was higher ($p < 0.05$) than that of the packaged one (2.7) (Fig. 1). In contrast, there was no difference in the oxidation indices (from the surface [2.7] to the interior [1.0]) between the packaged and unpackaged 100-Mrad PE after the test. The 100-Mrad PE that was age-accelerated in air for 1 year exhibited rapid oxidative degradation (oxidation index, 7) for the first 100 days and then exhibited almost no further oxidation (Fig. 2). In contrast, the 100-Mrad PE age-accelerated in saline exhibited almost no degradation (oxidation index, 1) after 1 year. The 100-Mrad PE exhibited some oxidation immediately after sterilization because it had been sterilized with gamma irradiation in air. The residual free-radical concentrations of packaged and unpackaged 100-Mrad PE were 4.5×10^{16} spins/g and 3.5×10^{16} spins/g, respectively (Fig. 3). In contrast, the

Fig. 1 Oxidation indices of test and load-soak (control) samples of 100-Mrad PE shelf-aged either packaged in triple PE packages or unpackaged for 30 years ($n = 1$, total four cups). The oxidation index of the unpackaged 100-Mrad PE surface was higher than that of the packaged one.

Fig. 2 Oxidation indices of 100-Mrad PE age-accelerated in air and in saline for 1 year ($n = 3$). The 100-Mrad PE in air exhibited rapid oxidative degradation. In contrast, the 100-Mrad PE in saline exhibited almost no degradation after 1 year.

Fig. 3 Residual free-radical concentrations of shelf-aged and retrieved 100-Mrad PE ($n = 3$). *Data obtained from reference 21. The residual free-radical concentration of packaged 100-Mrad PE was higher than that of the unpackaged one.

initial free-radical concentration of 100-Mrad PE was 11.9×10^{16} spins/g and the residual free-radical concentration of retrieved 100-Mrad PE was 4.5×10^{16} spins/g [20]. The ESR results revealed little difference in the residual free-radical concentrations between the shelf-aged and retrieved 100-Mrad PE. Both the weight loss and the linear wear of the unpackaged 100-Mrad PE cups were greater than these of the packaged 100-Mrad PE cups (Fig. 4) in the hip simulator test.

The packaged 100-Mrad PE cup exhibited high wear resistance with a (steady) wear rate of $0.50 \text{ mg}/10^6$ cycles. In contrast, the unpackaged 100-Mrad PE exhibited an extremely high initial wear rate of $187.9 \text{ mg}/10^6$ cycles over the first 0.25×10^6 cycles with a subsequently reduced wear rate of $5.0 \text{ mg}/10^6$ cycles after 5×10^6

Fig. 4A–B Wear properties of shelf-aged 100-Mrad PE, including (A) weight change and (B) linear wear ($n = 1$). *Data obtained from reference 12. The packaged 100-Mrad PE cup exhibited high wear resistance; in contrast, the unpackaged 100-Mrad PE exhibited an extremely high initial wear rate. For the first 0.25×10^6 cycles, a steep increase of approximately 0.2 mm was observed in the linear wear, followed by a leveling off with a tendency toward gradual increase over time.

cycles. For the first 0.25×10^6 cycles, a steep increase of approximately 0.2 mm was observed in the linear wear followed by a leveling off with a tendency toward a gradual increase over time.

Both the ECD and the aspect ratio were higher ($p < 0.001$) in the unpackaged 100-Mrad PE than in the

packaged one at all hip simulator testing intervals (Table 1). The ECD of unpackaged 100-Mrad PE gradually decreased ($p < 0.001$) with increasing testing intervals. The aspect ratio of the wear particles tended to be higher ($p < 0.05$) in the initial wear ($0\text{--}0.25 \times 10^6$ cycles) than in the steady wear ($4.5\text{--}5.0 \times 10^6$ cycles) for both the packaged and unpackaged 100-Mrad PE.

Discussion

The current study aimed to examine the influence of aging conditions on the in vivo degradation and wear resistance of gamma-irradiated UHMWPE by investigating the wear and oxidation of 100-Mrad PE cups shelf-aged with or without packages for 30 years.

We cannot definitively state whether and to what extent the differences in changes of some properties during the shelf-aging occur because we had so few 100-Mrad PE cups which had been aged for a long duration. However, because the data are unique, we believe the results useful. There are a few previous studies on gamma-irradiated UHMWPE aged for a short duration that have attempted to examine the influence of the aging environment on the performance [2, 11, 26]; therefore the values we found may not be comparable to those in the literature. To gain a better understanding of the retrieved 100-Mrad PE cups and/or gamma-irradiated UHMWPE cups, it is necessary to study statistically with a greater number of such cups.

The cross-linking and degradation reactions of UHMWPE are governed by free-radical reaction pathways [3]. For the reactions to proceed, free radicals must be formed in the PE by high-energy irradiation. Because the 100-Mrad gamma ray is an extremely high-energy beam, homolysis with the production of alkyl radicals could occur in PE (Fig. 3). Therefore, 100-Mrad PE should contain a large amount of free radicals in the polymer. In the case of unpackaged 100-Mrad PE, the PE surface was exposed to air for a long duration, which should have promoted the reaction of residual free radicals in the PE with oxygen

Table 1. Equivalent circle diameters and aspect ratios of shelf-aged 100-Mrad polyethylene in various hip simulator testing intervals compared with retrieved 100-Mrad polyethylene

Sample	Testing interval ($\times 10^6$ cycles)	ECD (μm)	Aspect ratio
Shelf-aged			
Packaged	0–0.25	0.22 (0.11–1.06)	1.35 (1.00–6.00)
	4.5–5.0	0.20 (0.11–0.56)	1.27 (1.00–3.20)
Unpackaged	0–0.25	0.29 (0.11–1.40)	1.54 (1.00–7.00)
	4.5–5.0	0.24 (0.11–1.03)	1.44 (1.00–4.48)
Retrieved*		(0.57–0.73)	(1.40–1.54)

Values are expressed as averages with ranges in parentheses; *data from reference 11; ECD = equivalent circle diameter.

Fig. 5 Comparison of oxidation indices between shelf-aged 100-Mrad PE and retrieved 100-Mrad PE. Each point on the figure shows the oxidation index of each specimen. *Data obtained from reference 13. The oxidation index of 100-Mrad PE was lower in vivo (retrieved) than in vitro (shelf-aged).

from the air to produce ketones and carboxylic acids, resulting in noticeable oxidative degradation (Fig. 1).

Previous studies report gamma-sterilized PE containing free radicals degrade with substantial oxidation in vivo [10, 11, 18]. We found the oxidation index of the degraded PE was lower in vivo (retrieved) than in vitro (shelf-aged) (Fig. 5). It has also been reported the oxygen content might be almost zero in the body [11, 24], and the oxidation index is lower in worn compared to unworn areas of retrieved PE [10, 11, 21]. Therefore, although the oxidative degradation of PE in vivo is related to the surrounding oxygen concentration, ie, that of the body fluid, it does not appear to be the main factor determining the degradation. Currier et al. [4] and Sychterz et al. [23] reported the shelf storage time before implantation is an important factor in oxidative degradation. We believe the shelf storage time and conditions in vitro are more important factors in determining the oxidative degradation than factors in vivo because during accelerated-aging testing, the 100-Mrad PE aged in air exhibited more oxidative degradation than that aged in saline, which prevented exposure to oxygen.

We found the wear rates of 100-Mrad PE cups that had been shelf-aged for 30 years were very low and consistent with the excellent clinical results observed with 100-Mrad PE implanted for more than 30 years [9, 27]. However, the initial wear rate of $187.9 \text{ mg}/10^6$ cycles in unpackaged 100-Mrad PE was extremely high as compared with that of packaged 100-Mrad PE. In a previous hip simulator study, the wear rate of 100-Mrad PE was also as low as $-2.22 \text{ mg}/10^6$ cycles and could be considered as zero [19]. Therefore, it appears the extraordinarily high initial wear rate of unpackaged 100-Mrad PE is the result of the oxidation of the PE surface during long-term shelf aging.

We observed the packaged 100-Mrad PE had a noticeably low wear rate in both the initial and steady wear

intervals. According to previous studies, UHMWPE stored in an inert gas (eg, nitrogen or argon) or a vacuum exhibit very little oxidative degradation [2, 16]. Although the shielding of packaged 100-Mrad PE from oxygen was not perfect in our study because the material was plastic-packaged in air, the triple PE packaging should have prevented the inflow of new air, thus preventing further oxidation. This suggests the packaged 100-Mrad PE had already shifted to a steady wear state before reaching 2.5×10^6 cycles. However, this was not the case for unpackaged PE. The packaged 100-Mrad PE may have attained a steady wear state earlier than the unpackaged one because it has a significantly thinner oxidative degradation layer.

Based on the study by McKellop et al. [16] we predicted the wear rate of the age-accelerated conventional UHMWPE would be approximately $70 \text{ mg}/10^6$ cycles. The steady wear rates of both packaged and unpackaged 100-Mrad PE in this study were considerably lower than that value. This indicates 100-Mrad (1000 kGy) gamma irradiation had the additional effect of improving the wear resistance; in other words, the high cross-linking of PE by high-energy irradiation could increase the wear resistance even if oxidative degradation had occurred.

Both packaged and unpackaged 100-Mrad PE exhibited low wear rates that were comparable to those observed clinically with 100-Mrad PE [17]. The worn surfaces were quite smooth for all the 100-Mrad PE cups. Such smooth surfaces might have formed as a result of stable wear performance over a long duration. The aspect ratio of wear particles in our study was almost equal to that of in vivo wear particles (1.4–1.5) [9], although the ECD was smaller. However, in clinical results [18], the oxidative degradation of 100-Mrad PE was hardly noticeable, possibly as a result of the lower concentration of dissolved oxygen in vivo than that of gaseous oxygen in air (Fig. 5). The finding of a larger ECD despite lower oxidative degradation in vivo can be explained by assuming the smaller wear particles were more likely phagocytosed by macrophages in vivo and dissipated.

Since 1998, several different highly cross-linked PE cups irradiated with a dose of 50 to 105 kGy have been produced and used extensively [15]. However, the followup period of such cups is slightly less than 10 years. In previous studies, we reported the long-term clinical wear of 100-Mrad PE cups was lower than that of conventional PE. We expect the highly cross-linked polyethylene cup will exhibit favorably low and steady wear similar to the 100-Mrad PE cup in clinical studies, although a detailed followup is obviously necessary.

Our data suggest gamma irradiation of UHMWPE at 100-Mrad improves wear resistance in vitro and in vivo. The high crosslinking of PE resulting from high-dose

irradiation might contribute to the improvement of wear resistance. Shelf storage conditions, which may affect the surface oxidation, influence the wear resistance of gamma-irradiated UHMWPE acetabular components.

Acknowledgments We thank Takuji Shikita, MD, Hisashi Igaki, PhD, and the research group of Mizuho Medical Instruments Ltd for their cooperation in the development of 100-Mrad PE. We also express special thanks to the engineers of the Research Division of Japan Medical Materials Corp for their technical assistance.

References

- Awatani J, Hashimoto M. Effect of radiation in the surface layer of polyethylene samples [in Japanese]. *J Soc Mater Sci*. 1966;15:108–113.
- Buchanan FJ, White JR, Sim B, Downes S. The influence of gamma irradiation and aging on degradation mechanisms of ultra-high molecular weight polyethylene. *J Mater Sci Mater Med*. 2001;12:29–37.
- Costa L, Luda MP, Trossarelli L, Brach del Prever EM, Crova M, Gallinaro P. Oxidation in orthopaedic UHMWPE sterilized by gamma-radiation and ethylene oxide. *Biomaterials*. 1998;19:659–668.
- Currier BH, Currier JH, Collier JP, Mayor MB, Scott RD. Shelf life and in vivo duration: impacts on performance of tibial bearings. *Clin Orthop Relat Res*. 1997;342:111–122.
- Digas G, Thanner J, Nivbrant B, Rohrl S, Strom H, Karrholm J. Increase in early polyethylene wear after sterilization with ethylene oxide: radiostereometric analyses of 201 total hips. *Acta Orthop Scand*. 2003;74:531–541.
- Dorr LD, Wan Z, Shahrdrar C, Sirianni L, Boutary M, Yun A. Clinical performance of a Durasul highly cross-linked polyethylene acetabular liner for total hip arthroplasty at five years. *J Bone Joint Surg Am*. 2005;87:1816–1821.
- Engh CA, Sychterz CJ, Engh CA Jr. Conventional ultra-high molecular weight polyethylene: a gold standard of sorts. *Instr Course Lect*. 2005;54:183–187.
- Goldman M, Pruitt L. Comparison of the effects of gamma radiation and low temperature hydrogen peroxide gas plasma sterilization on the molecular structure, fatigue resistance, and wear behavior of UHMWPE. *J Biomed Mater Res*. 1998;40:378–384.
- Iwaki H, Minoda Y, Kobayashi A, Kadoya Y, Ohashi H, Oonishi H, Yamano Y. In vivo quantitative analysis of highly crosslinked polyethylene particles in total hip replacements. *J Bone Joint Surg Br*. 2004;86(Suppl 4):405. Abstract.
- Kurtz SM, Hozack W, Turner J, Purtill J, MacDonald D, Sharkey P, Parvizi J, Manley M, Rothman R. Mechanical properties of retrieved highly cross-linked crossfire liners after short-term implantation. *J Arthroplasty*. 2005;20:840–849.
- Kurtz SM, Rimnac CM, Hozack WJ, Turner J, Marcolongo M, Goldberg VM, Kraay MJ, Edidin AA. In vivo degradation of polyethylene liners after gamma sterilization in air. *J Bone Joint Surg Am*. 2005;87:815–823.
- Kyomoto M, Ueno M, Kim SC, Oonishi H, Oonishi H. Wear of '100-Mrad' cross-linked polyethylene: effects of packaging after 30 years real-time shelf-aging. *J Biomat Sci Polym Ed*. 2007;18:59–70.
- Manning DW, Chiang PP, Martell JM, Galante JO, Harris WH. In vivo comparative wear study of traditional and highly cross-linked polyethylene in total hip arthroplasty. *J Arthroplasty*. 2005;20:880–886.
- McKellop HA, Shen FW, Campbell P, Ota T. Effect of molecular weight, calcium stearate, and sterilization methods on the wear of ultra high molecular weight polyethylene acetabular cups in a hip joint simulator. *J Orthop Res*. 1999;17:329–339.
- McKellop H, Shen FW, Lu B, Campbell P, Salovey R. Development of an extremely wear-resistant ultra high molecular weight polyethylene for total hip replacements. *J Orthop Res*. 1999;17:157–167.
- McKellop H, Shen FW, Lu B, Campbell P, Salovey R. Effect of sterilization method and other modifications on the wear resistance of acetabular cups made of ultra-high molecular weight polyethylene: a hip-simulator study. *J Bone Joint Surg Am*. 2000;82:1708–1725.
- Oonishi H, Clarke IC, Good VD, Tsuji E, Ikada Y, Ishimaru H, Tateishi T, Fujisawa A, Masuda S, Kumakura M. Low-wear effect of high-dose gamma-irradiated cross-linked polyethylene in total hip prostheses In: Imura S, Wada M, Omori H, eds. *Joint Arthroplasty*. Tokyo, Japan: Springer-Verlag Telos; 1999:97–108.
- Oonishi H, Clarke IC, Masuda S, Amino H. Study of retrieved acetabular sockets made from high-dose, cross-linked polyethylene. *J Arthroplasty*. 2001;16(Suppl 1):129–133.
- Oonishi H, Clarke IC, Yamamoto K, Masaoka T, Fujisawa A, Masuda S. Assessment of wear in extensively irradiated UHMWPE cups in simulator studies. *J Biomed Mater Res A*. 2004;68:52–60.
- Oonishi H, Kadoya Y. Wear of high-dose gamma-irradiated polyethylene in total hip replacements. *J Orthop Sci*. 2000;5:223–228.
- Oonishi H, Kadoya Y, Masuda S. Gamma-irradiated cross-linked polyethylene in total hip replacements—analysis of retrieved sockets after long-term implantation. *J Biomed Mater Res*. 2001;58:167–171.
- Shikita T. Wear and lubrication in total hip arthroplasty [in Japanese]. *Saigaiigaku*. 1972;15:653–696.
- Sychterz CJ, Young AM, Orishimo K, Engh CA. The relationship between shelf life and in vivo wear for polyethylene acetabular liners. *J Arthroplasty*. 2005;20:168–173.
- Treuhaft PS, McCarty DJ. Synovial fluid pH, lactate, oxygen and carbon dioxide partial pressure in various joint diseases. *Arthritis Rheum*. 1971;14:475–484.
- Wang A, Sun DC, Yau SS, Edwards B, Sokol M, Essner A, Polineni VK, Stark C, Dumbleton JH. Orientation softening in the deformation and wear of ultra-high molecular weight polyethylene. *Wear*. 1997;203:230–241.
- Willie BM, Ashrafi S, Alajbegovic S, Burnett T, Bloebaum RD. Quantifying the effect of resin type and sterilization method on the degradation of ultrahigh molecular weight polyethylene after 4 years of real-time shelf aging. *J Biomed Mater Res A*. 2004;69:477–489.
- Yamamoto K, Masaoka T, Manaka M, Oonishi H, Clarke I, Shoji H, Kawanabe K, Imakiire A. Micro-wear features on unique 100-Mrad cups: two retrieved cups compared to hip simulator wear study. *Acta Orthop Scand*. 2004;75:134–141.