T. J. S. Puolakka · J. T. Keränen · K. A. Juhola
K. J. J. Pajamäki · P. J. Halonen · J. K. Nevalainen
V. Saikko · M. U. K. Lehto · M. Järvinen

Increased volumetric wear of polyethylene liners with more than 3 years of shelf-life time

Accepted: 19 February 2003 / Published online: 1 April 2003
© Springer-Verlag 2003

Abstract We analyzed 20 retrieved gamma-sterilized polyethylene liners (Biomet Hexloc). The long-term durability varied significantly depending on shelf-life time before implantation. Liners with a shelf-life time of 3 years or more evinced significantly (P 0.002) higher volumetric wear than those with a shelf life time less than 3 years. Infrared spectroscopy and scanning calorimetry showed that all explanted implants underwent substantial in vivo oxidation and crystallization. The oxidative ageing of polyethylene renders the polyethylene liner susceptible to severe wear. Scanning electron microscopy of the bearing surface of the liner revealed abrasive wear as a dominant mechanism. Moreover, poor acetabular design produces excessively thin liners, substandard locking mechanism, and backside wear of the liner. The primary reason for severe wear in the Hexloc liner was poor modular design and oxidative degradation of the polyethylene.

Résumé Nous avons analysé 20 inserts acetabulaires de polyéthylène gamma—stérilisé (Biomet Hexloc) explantés. La durabilité à long terme a varié considérablement selon la durée de stockage avant implantation. Les inserts avec un temps de stockage de trois années ou plus ont montré une usure volumétrique notablement plus élevée (P 0.002) que ceux avec un temps de stockage au-dessous de trois années. La spectroscopie infrarouge et l'étude calorimétrique ont montré que tous les inserts explantés ont subi une substantielle oxydation et cristallisation in vivo. L'oxydation qui vieillit le polyéthylène rend l'insert prédisposé à une usure sévère. L'étude en microscopie électronique de la surface de l'insert a révélé une usure abrasive comme mécanisme dominant. De plus, de mauvais dessins acétabulaires ont conduit à des inserts minces, des mécanismes médiocres de fixation, et des usures de la face profonde de l'insert. La raison fondamentale de l'usure sévère de l'insert Hexloc était une mauvaise conception du système modulaire et une dégradation oxydative du polyéthylène.

T. J. S. Puolakka · K. J. J. Pajamäki · P. J. Halonen · M. Järvinen
Division of Orthopaedics, Department of Surgery,
Tampere University Hospital, P.O. Box 2000,
33521 Tampere, Finland

T. J. S. Puolakka · K. J. J. Pajamäki · P. J. Halonen · M. Järvinen
Medical School, University of Tampere, P.O. Box 607,
33101 Tampere, Finland

J. T. Keränen · K. A. Juhola
Institute of Materials Science, Tampere University of Technology,
P.O. Box 589, 33101 Tampere, Finland

J. K. Nevalainen
National Agency for Medicine, P.O. Box 55,
00301 Helsinki, Finland

V. Saikko
Department of Mechanical Engineering,
Helsinki University of Technology, P.O. Box 4300,
02015 HUT, Finland

T. J. S. Puolakka (✉) · K. J. J. Pajamäki · P. J. Halonen
M. U. K. Lehto
Coxa Hospital for Joint Replacement, P.O. Box 652,
33101 Tampere, Finland
e-mail: ygit@yahoo.com
Tel.: +358-3-31178086, Fax: +358-3-31178090

Introduction

At present, polyethylene debris and debris-induced osteolysis constitutes the main problem in total hip replacement (THR) arthroplasty [5]. One means of improving the survival time of THR was a modular polyethylene liner with a press-fit porous-coated hemispherical metal shell introduced in widespread clinical practice in the late 1980s. In most cases, the 3-to- 5-year short-term national arthroplasty register results gave promise of good clinical outcome. This notwithstanding, actual long-term register results usually turn out to be significantly poorer than expected [11, 13]. An insufficient locking mechanism between acetabular components has been seen to cause motion between the polyethylene liner and the metal shell, with concomitant wear of the liner and polyethylene debris formation [18]. Gamma irradiation of the liner in air induces significant changes in the polyethylene properties and results in severe liner wear [8]. In ad-

dition, prolonged shelf-life time of polyethylene components has an adverse effect on arthroplasty survival [1]. We have previously reported alarming wear of the Hexloc liner of the cementless porous-coated Biomet Universal cup [12]. To avoid substandard products in the future, it will be necessary to conduct retrieval studies of the revised components. The aim of this study was to analyze material and design issues related to 20 retrieved Hexloc liners and evaluate factors leading to poor clinical outcome of these THRs.

Materials and methods

The 20 retrieved ultra-high-molecular-weight polyethylene (UHMWPE) liners analyzed were the so-called modular Hexloc hi-wall design for use with the Universal acetabular shell (Biomet, Warsaw, IN, USA). According to information obtained from the manufacturer, UHMWPE liners were machined from extruded Hostalen GUR-415 bar (Hoechst AG/Aventis S.A., Strasbourg, France), except liner number 5, which was made of Hostalen GUR-412 or Hifax 1900 materials. The liners were gamma-sterilized in air with a dose of 25–30 kGy.

In three cases, a zirconia ceramic head was used on the femoral side, while in all other cases a cobalt-chromium alloy (CoCr) head was used. The size of the head was 28 mm in 11 cases and 32 mm in nine. The femoral stem was a noncollared cementless Bi-Metric stem (Biomet, Warsaw, IN, USA) in every case. Seventeen liners were revised with corresponding acetabular shells, but in three cases only, the polyethylene liner component was changed, leaving the metal acetabulum in place. In all revisions, the femoral head was replaced. In two cases of infection, the well-fixed Bi-Metric stem was also removed in the first-stage operation. Preoperative and peroperative findings and the indication for revision arthroplasty were recorded. Demographic patient and component data are presented in Table 1.

All liners were subjected to an initial visual inspection and assessment under a stereomicroscope before further measurements.

Notes were made of any visible fracture, surface damage, backside wear, corrosion, abrasion, or other changes. Volumetric liner measurements were carried out using a FARO Silver (FARO Inc., Lake Mary, FL, USA) three-dimensional (3D) coordinate measuring machine (CMM) equipped with a mechanical stylus tip of 1.5 mm radius. Three-dimensional scanning allows accurate digitizing of a worn surface of an explanted liner. The worn interior surface of each liner was measured by taking 3D data points around the inner surface. The AnthroCam program (FARO Inc.) was used to convert the scanned data points to a 3D surface model using an initial graphics exchange specification (IGES) file format. The IGES surface model was transferred to the Surfacar program (FARO Inc.) and changes in the liner's internal volume were calculated using a standard computer-aided design (CAD) program.

After stereomicroscopic assessment and CMM measuring, the liners were cut into two halves perpendicular to the ridge area. One half of the sample was prepared for scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) studies. SEM specimens were further prepared using standard specimen preparation techniques, i.e., diamond saw cutting and gold sputtering. Thereafter, the worn liner bearing surface morphology was examined using a Philips XL 30 SEM (FEI, Eindhoven, The Netherlands) equipped with an EDAX DX-4 EDS microanalysis system (EDAX Inc., Mahwah, NJ, USA). The other half of the liner was prepared for transmission light microscopy observation, crystallinity determination, and oxidation index measurements. For this purpose, 200- μ m thick cross-section slices were cut from the liner perpendicular to the bearing surface using microtomy.

The crystallinity of samples was measured on a PerkinElmer DSC 7 (PerkinElmer Inc., Wellesley, MA, USA) differential scanning calorimeter (DSC). A double-scan procedure was adopted in which each sample was heated at a rate of 20 K min⁻¹ from 30 to 200°C followed by fast cooling back to 30°C at a rate of 200 K min⁻¹. For each sample, the percentage of crystallinity was estimated from the measured enthalpy of fusion during the first heating cycle using a reference value of 289.74 J g⁻¹ for fully crystalline UHMWPE [9].

Oxidative degradation of UHMWPE liners was measured by Fourier Transform Infrared Spectrometry (FTIR). A PerkinElmer

Table 1 Demographic data of patients and components. *BMI* body mass index; *CoCr* cobalt-chromium

Case	Age (years)	Weight (kg)	Length (cm)	BMI	Gender 1= male 2= female	Duration in situ (years)	Head diameter (mm)	Type of head	Shell diameter (mm)	Socket abduction angle	Number of screws	Initial polyethylene thickness (mm)	Reason for revision
1	62	112	179	35.0	1	3.5	32	CoCr	56	38	1	2.53	Wear
2	37	63	163	23.7	2	6.8	28	CoCr	50	39	0	3.61	Wear
3	36	77	173	25.7	2	4.1	28	Zirconia	52	45	1	3.61	Wear
4	61	58	156	23.8	2	6.7	28	CoCr	48	42	0	3.39	Dislocation
5	60	79	180	24.4	1	5.2	32	CoCr	56	46	0	2.53	Wear
6	64	89	161	34.3	2	6.3	28	CoCr	52	63	0	3.61	Dislocation
7	63	91	180	28.1	1	5.8	28	CoCr	54	32	0	4.53	Dislocation
8	46	51	160	19.9	2	4.5	32	CoCr	58	47	2	4.47	Wear
9	59	89	184	26.3	1	5.9	32	CoCr	60	38	0	4.47	Wear
10	32	92	166	33.4	2	6.5	28	Zirconia	50	50	1	3.61	Wear
11	59	58	159	22.9	2	6.6	28	CoCr	50	46	0	3.61	Wear
12	56	72	172	24.3	1	6.8	28	CoCr	50	40	0	3.61	Dislocation
13	61	85	184	25.1	1	7.2	32	CoCr	56	44	0	2.53	Wear
14	66	78	175	25.5	1	5.9	28	CoCr	52	53	0	3.61	Dislocation
15	44	58	160	22.7	2	5.6	32	CoCr	56	56	2	2.53	Wear
16	51	64	154	27.0	2	5.5	32	CoCr	56	47	2	2.53	Infection
17	71	75	163	28.2	2	4.2	32	CoCr	62	32	2	4.47	Infection
18	36	50	155	20.8	2	8.4	28	CoCr	48	48	1	3.39	Wear
19	51	52	160	20.3	2	7.6	28	CoCr	46	59	0	3.39	Wear
20	55	90	175	29.4	1	4.4	32	Zirconia	68	49	3	6.47	Wear

1725X spectrometer (PerkinElmer Inc.) was used, and spectra were collected using eight scan summations and a resolution of 4.0 cm^{-1} . Each liner was measured twice using a different 200- μm thick microtomy sample. Each spectrum showed a carbonyl ($\text{C}=\text{O}$) absorption peak centered at 1718 cm^{-1} . C-H absorption centered at $1,368\text{ cm}^{-1}$ was selected as the reference peak, and the oxidation index (OI) was calculated as a ratio of integrated areas of these two peaks [8].

Surface roughness of explanted femoral heads was measured with a UBM Microfocus COMPACT laser profilometer (NanoFocus Inc., Sunnyvale, CA, USA) using 1.75 mm evaluation length. During one linescan, 1,750 data points were measured. At least ten measurements were made of each explanted femoral head in different directions over the pole. The laser profilometer is a noncontact surface roughness measurement technique known to result in average surface roughness R_a values four-to-six times higher compared with a standard contact method [17]. The laser profilometer was therefore carefully calibrated with a known roughness standard to render roughness measurements in this work comparable to reported values measured by a traditional contact diamond stylus method.

Statistics

Means and standard deviation were used with normally distributed variables. Medians and range were used for variables with skewed distributions. Differences between groups in continuous variables were tested by means of independent sample *t*-tests, and for variables with skewed distributions, the Mann-Whitney *U* test was used. Data were analyzed using SPSS for Windows statistical software version 10.1.

Results

Visual assessment and stereomicroscopy

The polyethylene liner was manifestly worn out or fractured in nine cases. Cracks were observed on the rim, and a concentration of the cracks was present around the rim of each component. In three out of five dislocation cases, the liner was also fractured. Three retrieved liners were so severely damaged that the superior part of the bearing surface of the polyethylene was completely worn out, and there was metal-on-metal contact between femoral head and metal shell. This had caused wear of the metal shell (Fig. 1) and severe metallosis in the joint tissue. All revised liners appeared slightly discolored. Visual inspection of the liner revealed burnishing on the back surface of polyethylene and titanium particles some few hundred micrometers in size entrapped on the backside of the liner in all cases, as shown in Fig. 2. Occasionally, a few titanium particles were also observed on the actual bearing surface of the liner, but the number of visible particles was smaller than on the backside. Cold flow (i.e., creep) of the polyethylene on the backside of the liner appeared in areas situated over the open screw hole of the metallic shell in all cases. The polyethylene tended to flow into the screw holes and form a 1-to-2-mm high node on the backside of the liner, as shown in Fig. 3. Moreover, deformation and wear was seen at the notches of the hexagonal locking mechanism, and the central snap lock tabs were fractured in all liners.

Fig. 1 Photograph of an acetabular liner showing that the superior part of the liner was completely worn away and the metal shell under the liner was significantly worn also. Implantation time was 62 months, and the femoral head was made of cobalt-chromium alloy (CoCr) alloy

Fig. 2 Photograph of an acetabular liner seen from the backside, showing titanium particles entrapped in the liner surface. Implantation time was 79 months, and the femoral head was made of zirconia

Fig. 3 The backside of the liner is showing nodes that correspond to the cold flow of polyethylene into the metal screw holes. The superior part of the liner was worn away and the rim was displaced. The central snap-lock tabs were fractured. Implantation time was 84 months, and the femoral head was made of cobalt-chromium alloy (CoCr) alloy

Table 2 Shelf life, volumetric wear, volumetric wear rate, crystallinity, and oxidation index of polyethylene liner (1,370 cm⁻¹ normalization) and average roughness R_a of femoral head

Case No.	Shelf life (months)	Volumetric wear (mm ³)	Volumetric wear rate (mm ³ /year)	Crystallinity (%)	Oxidation index (OI)	Roughness R_a of head (μm)
1	40	2,465	704	65	0.82	0.02
2	10	1,774	263	71	0.90	0.03
3	15	1,406	344	67	0.86	0.04
4	15	1,262	189	64	0.92	0.03
5	44	2,361	457	72	1.03	0.05
6	3	1,627	260	79	0.56	0.29
7	4	1,308	224	66	0.60	0.24
8	36	1,995	443	71	0.84	0.02
9	Cannot be traced	2,180	368	65	0.89	0.04
10	Cannot be traced	1,782	274	61	0.91	0.02
11	Cannot be traced	1,396	212	60	0.80	0.01
12	25	738	108	63	0.88	0.03
13	Cannot be traced	1,560	218	64	0.60	0.01
14	Cannot be traced	1,015	172	63	0.64	0.14
15	17	1,560	279	75	0.86	0.02
16	7	230	42	70	0.63	0.04
17	Cannot be traced	566	136	62	1.02	0.01
18	Cannot be traced	1,377	164	83	0.96	0.04
19	Cannot be traced	896	118	66	0.89	0.02
20	Cannot be traced	4,086	925	69	0.75	0.03

Fig. 4 Increase of the volumetric wear rate with increasing shelf life of the ultra-high-molecular-weight polyethylene (UHMWPE) liner

Wear measurements

Wear measurements are summarized in Table 2. The average volumetric wear measured by CMM was 1,579 mm³ (SD 824). The average volumetric wear rate was 295 mm³/year (SD 210). Thirty-two-millimeter heads evinced significantly ($P=0.047$) greater wear than 28-mm heads, 397 mm³/year (SD 278) and 211 mm³/year

(SD 71), respectively. There was a correlation between shelf-life time and volumetric wear rate (Fig. 4). Liners with a shelf-life time of 3 years or more had a significantly ($P=0.002$) higher volumetric wear rate than those with a shelf-life time less than 3 years. Average volumetric wear was 535 mm³/year (SD 147) and 214 mm³/year (SD 98), respectively. It should be mentioned that there were 11 patient cases in which implant shelf-life could be traced. Average volumetric wear was significantly ($P=0.047$) greater in zirconia than in CoCr heads, with a mean of 515 mm³/year (SD 357) and 256 mm³/year (SD 161), respectively. There was no statistically significant correlation between volumetric wear and polyethylene thickness; acetabular component abduction angle; screw fixation; and patient age, gender, weight, height, or body mass index (BMI).

Femoral head and liner surface topography

Median surface roughness of explanted femoral heads was 0.03 μm (range 0.01–0.29 μm), as shown in Table 2. Average roughness of zirconia and CoCr heads was the same. Cases where dislocation of THR was the primary reason for revision had significantly ($P=0.024$) greater roughness than the others, the median R_a being 0.14 μm (range 0.03–0.29 μm) and 0.02 μm (0.01–0.05 μm), respectively. SEM examination of the liner revealed tearing, scoring, and open porosity of the bearing surfaces. Grooves and fringe were the most marked features in the liner load-bearing zone, as shown in Figs. 5 and 6, respectively. X-ray microanalysis (EDS) revealed streaks of titanium alloy adhering to the surface of zirconia heads, which explains the grayish stripes on the load-

Fig. 5 Common appearance of bearing surface of the ultra-high-molecular-weight polyethylene (UHMWPE) liner showing grooves and open-surface porosity. Implantation time was 42 months, and the femoral head was made of cobalt-chromium (CoCr) alloy

Fig. 6 Common appearance of the bearing surface of the ultra-high-molecular-weight polyethylene (UHMWPE) liner showing fibrillar fringes. Implantation time was 54 months, and the femoral head was made of cobalt-chromium (CoCr) alloy

bearing area of the femoral zirconia head. Also, particles found on the backside of liners were identified by EDS microanalysis as a titanium alloy.

Oxidative degradation of ultra-high-molecular-weight polyethylene

results of FTIR and DSC measurements are summarized in Table 2. Mean crystallinity of retrieved liners was 68% (SD 6) and median oxidation index of liners was 0.86 (range 0.56–1.03). Crystallinity or oxidation index showed no correlation with volumetric wear rate. A typical transmission light microscopy image of 200 μm thick microtomy cross-section of a UHMWPE liner is shown in Fig. 7. All retrieved liners showed evidence of a sub-surface white band in the optical dark field micrographs.

Fig. 7 Optical transmission dark field micrograph of the microtomy cross-section of the ultra-high-molecular-weight polyethylene (UHMWPE) liner. At higher magnification, the white band appears as a trail of single particles that adhered poorly to the surrounding particles. The gap between particles and the surrounding matrix diffract visible transmission light under the microscope, resulting in the appearance of the so-called white band

Discussion

The average volumetric wear rate of all liners was 295 mm³/year, which is significantly more than that usually reported for well-functioning retrieved UHMWPE liners [17]. The 32-mm heads evinced greater wear than the 28-mm heads, and strictly from a wear perspective, the 32-mm heads are not to be preferred [10]. In this study, however, the volumetric wear rate in the case of 28-mm heads was equally unsatisfactory. A ceramic femoral head or small femoral head diameter does not safeguard against wear if the basic construction or material of the acetabular component is not functioning properly. Interestingly, the highest volumetric wear volume was measured in a case with a 32-mm zirconia femoral head and the thickest polyethylene liner wall in this study (i.e., 6.5 mm). One might expect that this particular modular THR combination would lead to only moderate wear of UHMWPE in optimum conditions. Zirconia heads have commonly been recommended because of their favorable surface characteristics, leading to less polyethylene wear in simulator studies [14, 16]. However, if the quality of the polyethylene is poor or the design of the modular acetabulum component is flimsy, the clinical outcome of THR with a zirconia head and modular UHMWPE liner could be extremely poor. Kim et al. [7] also found evidence in a clinical radiological study that wear of the modular polyethylene liner was worse with zirconia than with metallic CoCr femoral heads. It would thus not seem always beneficial to use more expensive zirconia heads in THRs if an insufficient locking mechanism of the modular liner and poor material quality of the UHMWPE liner lead to catastrophic wear of the polyethylene liner regardless of the femoral component.

We found a clear correlation between shelf-life time and the volumetric wear rate of UHMWPE liners. In lin-

ers with more than 3 years of shelf life, there was significantly higher volumetric wear than in those with shorter shelf-life time. In tibial components, Bohl et al. [1] observed the same adverse effect; a long-term shelf life of over 4 years induced a significantly poorer survival rate than a shorter shelf-life time. It is a matter of concern that there is no standard for minimum shelf-life time, neither in the FDA protocol in the United States nor in the CEN/ISO standard in Europe. In practice, many manufacturers voluntarily limit stock shelf life to 5 years in the Western market. Regardless, hospitals should pay attention to the shelf-life time of THRs purchased.

Unfortunately, gamma radiation in air was a commonly used sterilization method in the early 1990s and constitutes a universal feature of the first generation of metal-backed acetabular liner construction. All conventional UHMWPE components manufactured before the mid-1990s were rendered liable to progressive oxidative degeneration. Since then, virtually all manufacturers have altered their sterilization methods, employing ethylene oxide gas (EtO), gas plasma, or gamma sterilization in a low-oxygen environment (i.e., argon or nitrogen gas). This should delay the shelf-aging tendency of conventional UHMWPE components in the future.

However, recent retrieval studies of EtO-sterilized liners also show unexpected bulk oxidation of UHMWPE [2]. The explanted implants showed substantial in vivo oxidation, with an average OI of 0.82 (range 0.56–1.03). Kurtz et al. [8] reported that the average OI of the as-irradiated GUR 4150 rod stock was 0.232 based on the same $1,370\text{ cm}^{-1}$ normalization method used in this study. The average OI of an unused Hexloc liner with a shelf age of up to 12 years is 0.66 (SD 0.03). This would suggest that oxidation takes place in self-stored implants but to a lesser extent than in vivo.

The increase of OI is a direct consequence of radiation damage and shelf aging. It has been extensively documented that gamma radiation in air induces marked changes in the chemical and physical properties of UHMWPE and, what is of greater concern, the magnitude of aging increases with time [8]. The energy of gamma radiation breaks the C-C and C-H bonds in the polyethylene, resulting in chain scission and formation of free radicals. If oxygen is present, free radicals can react with it, resulting in additional chain scission. Since free radicals can persist in UHMWPE for years, chain scission tends to increase concomitant with shelf storage, i.e., time between sterilization and implantation. As oxidation and chain scission progress, shortening of polymer molecules increases the density and crystallinity of UHMWPE. In our study, there were marked increases in crystallinity in the retrieved liners, ranging from 60 to 83%. The as-synthesized GUR-415 UHMWPE typically has a crystallinity value of 58% [9]. Moreover, all retrieved liners showed an approximately 400- μm -wide white band typically about half a millimeter below the surface. At higher magnification, the white band appeared as a trail of single particles adhering poorly to the surrounding particles. SEM revealed open pores on the

bearing surface, which are also related to the incomplete fusion of polyethylene powder particles. Both microscopic findings also demonstrated the existence of degenerative aging of UHMWPE.

The average roughness R_a value of femoral heads was not as high as one might expect but corresponded to values found in the retrieved heads [3, 4, 6]. Titanium particles as a material are softer than the zirconia or CoCr alloy used in the femoral heads. It is therefore no surprise that the average femoral head was relatively smooth despite the fact that there were obviously titanium third bodies between the bearing surfaces in vivo. Electron microscopy brought out scratches and grooves on the bearing surface of the UHMWPE liner, indicating abrasive wear.

A fibrillar polyethylene fringe was another typical feature on the liner's load-bearing zone. Abrasive wear on the front side of the liner results in fringe formation and finally release of UHMWPE particles. Sometimes, the polyethylene fringes are related to the adhesive wear of UHMWPE reported in the literature. However, careful hip simulator studies of the UHMWPE liner against a roughened femoral head have shown that fringes are a characteristic wear pattern for abrasive wear, not for adhesive wear of UHMWPE [15].

Burnishing of the hexagonal locking mechanism notches and fracture of the central snap lock tabs in all liners suggest that movement between the liner and the metal shell backing occurred in vivo leading to backside wear of the liner [18]. The abrasive wear of severely oxidized UHMWPE is clearly one reason for the high wear rate in our study.

The wear of UHMWPE in THR is a multifactorial problem depending on device design, material properties, surgical technique, and patient risk factors. The primary reason for severe wear in the modular Hexloc liner was poor modular design and oxidative degradation of UHMWPE. Poor acetabular design leads to extraordinarily thin liners, substandard locking mechanism, and backside wear. Moreover, the open screw holes on the metallic shell offer an unobstructed migration route to the UHMWPE and titanium wear particles to the pelvis. This leads to adverse foreign body reactions, such as retroacetabular bone osteolysis. On the other hand, the conventional UHMWPE gamma sterilized in air is liable to progressive oxidative degradation and prolonged shelf-life time before implantation. Oxidative aging of UHMWPE makes the polyethylene liner susceptible to severe wear. The reason for the catastrophic wear of the modular Hexloc liner was thus, according to the present study, an unfortunate synergism of many inferior material and design factors.

Acknowledgments The authors thank Mr. Arto Muikku for CMM measurements and Dr. Tapio Tarvainen for helpful discussions in the course of this study. This work was supported by the Medical Research Fund of Tampere University Hospital and the Academy of Finland under Grant No. 44591.

References

1. Bohl JR, Bohl WR, Postak PD, Greenwald AS (1999) The Coventry Award. The effects of shelf life on clinical outcome for gamma sterilized polyethylene tibial components. *Clin Orthop* 367:28–38
2. Costa L, Jacobson K, Bracco P, Brach del Prever EM (2002) Oxidation of orthopaedic UHMWPE. *Biomaterials* 23:1613–1624
3. Hall RM, Unsworth A, Siney P, Wroblewski BM (1996) Wear in retrieved Charnley acetabular sockets. *Proc Inst Mech Eng* 210:197–207
4. Hall RM, Siney P, Unsworth A, Wroblewski BM (1997) The effect of surface topography of retrieved femoral heads on the wear of UHMWPE sockets. *Med Eng Phys* 19:711–719
5. Harris WH (2001) Wear and periprosthetic osteolysis: the problem. *Clin Orthop* 393:66–70
6. Isaac GH, Wroblewski BM, Atkinson JR, Dowson D (1992) A tribological study of retrieved hip prostheses. *Clin Orthop* 276:115–125
7. Kim YH, Kim JS, Cho SH (2001) A comparison of polyethylene wear in hips with cobalt-chrome or zirconia heads. A prospective, randomized study. *J Bone Joint Surg [Br]* 83:742–750
8. Kurtz SM, Muratoglu OK, Gsell R, Greer K, Shen FW, Cooper C, Buchanan FJ, Spiegelberg S, Yau SS, Edidin AA (2002) Interlaboratory validation of oxidation-index measurement methods for UHMWPE after long-term shelf aging. *J Biomed Mater Res (Appl Biomater)* 63:15–23
9. Li S, Burstein AH (1994) Ultra-high molecular weight polyethylene. The material and its use in total joint implants. *J. Bone Joint Surg [Am]* 76:1080–1090
10. Livermore J, Ilstrup D, Morrey B (1990) Effect of femoral head size on wear of the polyethylene acetabular component. *J Bone Joint Surg [Am]* 72:518–528
11. Puolakka TJS, Pajamäki KJJ, Pulkkinen PO, Nevalainen JK (1999) Poor survival of cementless Biomet total hip. A report on 1,047 hips from the Finnish Arthroplasty Register. *Acta Orthop Scand* 70:425–429
12. Puolakka TJS, Laine H-J, Moilanen TPS, Koivisto A-M, Pajamäki KJJ (2001) Alarming wear of the first-generation polyethylene liner of the cementless porous-coated Biomet Universal cup. 107 hips followed for mean of 6 years. *Acta Orthop Scand* 72:1–7
13. Puolakka TJS, Pajamäki KJJ, Halonen PJ, Pulkkinen PO, Paavolainen P, Nevalainen JK (2001) The Finnish Arthroplasty Register. Report of the hip register. *Acta Orthop Scand* 72:433–441
14. Saikko VO (1995) Wear of the polyethylene acetabular cup. The effect of head material, head diameter and cup thickness studied with a hip simulator. *Acta Orthop Scand* 66:501–506.
15. Saikko VO, Calonius O, Keränen J (2002) Wear of conventional and crosslinked ultrahigh molecular weight polyethylene acetabular cups against polished and roughened CoCr femoral heads in a biaxial hip simulator. *J Biomed Mater Res* 63:848–853
16. Smith SL, Unsworth A (1999) A comparison between gravimetric and volumetric techniques of wear measurement of UHMWPE acetabular cups against zirconia and cobalt-chromium-molybdenum femoral heads in a hip simulator. *Proc Inst Mech Eng (H)* 213:475–483
17. Sychterz CJ, Engh CAJr, Swope SW, McNulty DE, Engh CA (1999) Analysis of prosthetic femoral heads retrieved at autopsy. *Clin Orthop* 358:223–234
18. Williams VG II, Whiteside LA, White SE, McCarthy DS (1997) Fixation of ultra-high-molecular-weight polyethylene liners to metal-backed acetabular cups. *J Arthroplasty* 12:25–31