Biotribology of a vitamin E-stabilized polyethylene for hip arthroplasty – Influence of artificial ageing and third-body particles on wear

Thomas M. Grupp a,b,*, Melanie Holderied a, Marie Anne Mulliez a, Rouven Streller a, Marcus Jäger c, Wilhelm Blömer a, Sandra Utzschneider b

a, Aesculap AG Research & Development, Tuttingen, Germany
b, Ludwig Maximilians University Clinic for Orthopaedic Surgery, Campus Grosshadern, Munich, Germany
c, Clinic for Orthopaedic Surgery, University of Essen, Germany

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ABSTRACT

The objective of our study was to evaluate the influence of prolonged artificial ageing on oxidation resistance and the subsequent wear behaviour of vitamin E-stabilized, in comparison to standard and highly cross-linked remelted polyethylene inlays in total hip arthroplasty. Hip wear simulation was performed with three different polyethylene inlay materials (standard: γ-irradiation 30 kGy; highly cross-linked and remelted: γ-irradiation 75 kGy, EO; highly cross-linked and vitamin E (0.1%) blended: electron beam 80 kGy, EO) machined from GUR 1020 in articulation with ceramic and cobalt–chromium heads. All polyethylene inserts beneath the virgin references were subjected to prolonged artificial ageing (70 °C, pure oxygen at 5 bar) with a duration of 2, 4, 5 or 6 weeks. In conclusion, after 2 weeks of artificial ageing, standard polyethylene shows substantially increased wear due to oxidative degradation, whereas highly cross-linked remelted polyethylene has a higher oxidation resistance. However, after enhanced artificial ageing for 5 weeks, remelted XLPE also starts oxidate, in correlation with increased wear. Vitamin E-stabilized polyethylene is effective in preventing oxidation after irradiation cross-linking even under prolonged artificial ageing for up to 6 weeks, resulting in a constant wear behaviour.

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1. Introduction

The biological response to polyethylene wear particles released by orthopaedic implants is a key factor in periprosthetic osteolysis and subsequent implant loosening [1–5]. In hip wear simulations highly cross-linked polyethylenes (XLPE) have been shown to improve wear resistance and, for this reason, have been introduced as bearing materials in orthopaedic joint replacements [6–8]. After a decade of use in total hip arthroplasty, highly cross-linked polyethylenes are now clinically established as the material of choice for acetabular liners in articulation with ceramic heads [9–12].

These liners have been proved to reduce significantly wear [13–15] and osteolysis [15–18]. Analysing the incidence of acetabular osteolysis in young patients (25–55 years old) by computer tomography, with a mean follow-up of 7.2 years (range 5.1–10.9 years), Mall et al. [17] reported apparent osteolysis in 24% of the patients with standard polyethylene components compared to 2% in the XLPE group. In a systematic review of wear and osteolysis outcomes in hip arthroplasty, Kurtz et al. [15] calculated a mean linear rate of femoral head penetration of 0.042 mm year−1 for XLPE liners (n = 1503 hips, 28 studies) and of 0.137 mm year−1 for standard polyethylene (n = 695 hips, 18 studies). Based on a pooled odds ratio of 0.131 across nine studies, they estimated an 87% lower risk of osteolysis [15].

To improve the oxidation resistance, highly cross-linked polyethylenes have to be thermally treated by annealing or remelting after irradiation [6,7,19]. Annealing of XLPE substantially reduces the residual free radicals, but the remaining minor fraction still persists in the material, with the consequence of further oxidation [12]. Wannomae et al. [20] found in vivo oxidation by residual free radicals in irradiated and annealed XLPE acetabular components retrieved 4–33 months after implantation, a result corroborated by Kurtz et al. [21]. While annealing leads to the retention of the remaining oxidation potential, only post-irradiation remelting is effective at eliminating the residual free radicals [12]. However,
remelting substantially affects the mechanical properties of XLPE [21,22] due to the loss of crystallinity [16], a possible reason for structural material fatigue in vivo [24–26]. Furthermore Muratoglu et al. [27] described two potential mechanisms which might reduce the oxidative stability of irradiated and remelted XLPE in vivo – cyclic loading and absorption of liquids. Increasing oxidation leads to a concomitant decrease in cross-link density and increase in crystallinity [27] which, according to Carpentieri et al. [28], plays a major role on the post-irradiation oxidative effects of polyethylenes.

For this reason, the stabilization of highly cross-linked polyethylene by diffusion [22] or blending [29,30] of the antioxidant vitamin E was developed to enhance oxidation resistance [31] and improve fatigue strength by the avoidance of post-irradiation melting [16,32]. Highly cross-linked polyethylene stabilized by diffusion of vitamin E showed superior oxidation resistance, equivalent wear behaviour and enhanced mechanical properties in comparison to an irradiated and remelted XLPE with the same dose level (100 kGy) [16,22].

2. Objectives

The objective of our study was to evaluate the influence of prolonged artificial ageing on oxidation resistance and the subsequent wear behaviour of vitamin E-stabilized, in comparison to standard and highly cross-linked, remelted polyethylene, and the degradation effect of third-body particles on XLPE inlays in total hip arthroplasty.

3. Materials and methods

In vitro wear simulation was performed using acetabular cups (Plasmacup® DC Ø 52/54 mm, Aesculap AG Tuttlingen, Germany) made out of Ti6Al4 V alloy in combination with three different polyethylene inlay materials machined from GUR 1020. The standard polyethylene inlays (STD) were packed under nitrogen atmosphere and sterilized by γ-irradiation (30 ± 2 kGy). The highly cross-linked and remelted polyethylene inlays (REM) were cross-linked by γ-irradiation (75 kGy) and sterilized by ethylene oxide (EO). The highly cross-linked and vitamin E (0.1%) blended polyethylene inlays (VitE) were cross-linked by an electron beam (80 kGy) and sterilized by EO.

In the comparative wear simulation, the highly cross-linked polyethylene inlays (REM, VitE) were used at a size of Ø 36/52 mm and combined with modular heads of Ø 36 mm (taper 12/14) made out of zirconia toughened alumina ceramic (BIOLOX® delta, Aesculap AG, Tuttlingen, Germany) or out of CoCrMo alloy (Aesculap AG, Tuttlingen, Germany). The STD were used as the clinical established reference at a size of Ø 36/52 mm and combined with modular heads of Ø 36 (taper 12/14) made out of alumina ceramic (BIOLOX® forte, Aesculap AG, Tuttlingen, Germany).

All polyethylene inlays beneath the virgin reference components were subjected to artificial ageing according to ASTM F2003–02 (parameters: 70 °C, pure oxygen at 5 bar, duration 2, 4, 5 and 6 weeks). Therefore the inserts were put into a pressure vessel (Millipore Corp. 6700P05, Merck KgaA, Darmstadt, Germany) at room temperature that was filled with pure oxygen at an initial pressure of 5 bar (73 ± 1 psi), which was then oven heated to a target temperature of 70 °C to reach a target pressure of 5.79 bar (84 psi). At these conditions, one standard ageing cycle (2 weeks) has a duration of 336 h. All polyethylene inserts were soaked prior to wear simulation in serum-based test medium until the incremental mass change over 24 h was less than 1% of the previous cumulative mass change to allow for saturated fluid absorption (Table 1).

To determine the oxidation state of the polyethylene inserts after artificial ageing, slices were cut using a Microtome (Leica Microsystems Type RM2255, Wetzlar, Germany), stepwise in increments of 100 μm from the articulating surface down to 500 μm and at 1000 μm, and oxidation index measurements were performed by Fourier transform infrared spectroscopy (FTIR; Perkin Elmer Spectrum Image-Spotlight 200, Rodgau, Germany). For each absorbance spectrum, the total area of the peak absorptions between 1650 and 1850 cm⁻¹ (Aoxic) was calculated, together with the reference peak for polyethylene (between 1330 and 1396 cm⁻¹, Aref), for each reference inlay prior to wear testing. The oxidation index (OI) was calculated in accordance with ISO 5834–4:2005 by division of the area Aoxic/Aref.

3.1. In vitro wear simulation

In vitro wear simulation was performed on a customized 6 + 2-station servo-hydraulic hip simulator (EndoLab GmbH Thansau, Germany) with kinematic and load patterns according to ISO 14242–1:2012 (E).

Three acetabular cups per test group were fixed with epoxy resin and mounted on the wear test stations. In each test group a reference that was submitted only to axial force for loaded soak control was tested in parallel. The femoral heads were fixed via a stainless steel tube with a 12/14 taper connection. The STD, REM and VitE groups were tested through five million cycles with a frequency of 1 Hz in a lubricant of newborn calf serum (Biochrom AG, Berlin, Germany) diluted with deionized water to achieve the target protein content of 30 g l⁻¹. The lubricant was incubated at 37 °C, pH-stabilized with ethylene diamine tetraacetic acid and replaced at intervals of 0.5 million cycles. Patricine was added to prevent fungal decay.

To test for wear in the presence of third-body particulate debris, particles of poly(methyl methacrylate) (PMMA) bone cement with a mean size between 125 and 150 μm and a particle concentration of 5 g l⁻¹ were used. They were generated out of Palacos® R bone cement (Heraeus Medical, Wehrheim, Germany) containing zirconium dioxide as a radiopaque material. After the completion of 5 million cycles, the highly cross-linked polyethylene test groups in virgin condition (REMvirgin delta, REMvirgin CoCr, VitEvirgin delta, VitEvirgin CoC), were again tested for 3 million cycles under third-body conditions in articulation with BIOLOX® delta (REMthird-body delta, VitEthird-body delta) and CoCrMo (REMthird-body CoCr, VitEthird-body CoC) femoral heads of 36 mm diameter (Fig. 1).

At each measurement interval (0.5, 1, 2, 3, 4 and 5 million cycles for STD, REM and VitE groups and 5.5, 6.5, 7.5, 7.5 and 8 million cycles for REMthird-body and VitEthird-body groups), the devices were cleaned as prescribed in ISO 14242-2:2000(E) protocols for gravimetric wear assessment of hip joint articulations. Wear of the polyethylene inlays and of the modular femoral heads was determined gravimetrically using an analytical balance (Sartorius CPA225D, Göttingen, Germany) to a precision of 0.01 mg, taking air buoyancy and lubricant absorption into account. All bearing surfaces were inspected with a stereo microscope (Leica MZ 16, Bensheim, Germany). The component sets were rotated across stations after each half million cycles to minimize the effect of inter-station kinematic variability.

A geometrical assessment of plastic deformation (creep) and wear was performed after 5 million cycles for the test groups STD, REM and VitE with a three-dimensional measuring machine (Zeiss UMM850, Oberkochen, Germany) in a tactile measuring mode (1500 points per scan). The geometrical changes were displayed vertically to the transversal plane of the polyethylene inlays with a pseudocolour mode, the colours being spread between red = +0.05 mm and purple = −0.3 mm for the articulating surface of the polyethylene inlays.
The influence of artificial ageing on the wear behaviour of the different polyethylene materials, STD, REM and VitE, was evaluated statistically by a paired Student’s t-test. Due to the multiple-group comparisons, a Bonferroni correction was added ($\alpha_{local} = 0.00833$, $k = 6$) resulting in $\alpha_{local} < 0.00833$. To determine the wear amount under third-body conditions, an analysis of variance was carried out ($p = 0.05$), followed by a post hoc test (Scheffe $p = 0.05$) to differentiate between the head materials cobalt–chromium and ceramic.

Prior to the analysis, the normal distribution ($p$–$p$ plots) and the homogeneity of variance (Levene test) were verified (Statistica 10, StatSoft Europe GmbH, Hamburg, Germany).

### 4. Results

Prior to the in vitro wear simulation, after 2 weeks of ageing, the polyethylene inlays of STD, REM and VitE test groups had an oxidation index of 0.67 ± 0.12 for STDaged2, of 0.034 ± 0.027 for REMaged2 and of 0.046 ± 0.035 for VitEaged2, whereas, after 4 weeks of ageing, the mean OI was 4.48 ± 1.06 for STDaged4, 0.051 ± 0.037 for REMaged4 and 0.047 ± 0.038 for VitEaged4. After 6 weeks of artificial ageing, the mean OI had substantially increased to 0.47 ± 0.31 for REMaged6, but remained constant at 0.048 ± 0.041 for VitEaged6 (Fig. 2).

#### 4.1. In vitro wear simulation

The gravimetric wear rates in articulation with 36 mm ceramic heads significantly increased for STD inlays in correlation to the time of artificial ageing from 19.0 ± 0.6 mg per million cycles for STDvirgin forte to 30.3 ± 3.1 mg per million cycles for STDaged2 forte ($p = 0.007388$) and to 365.8 ± 37.2 mg per million cycles for STDaged4 forte ($p = 0.000086$). The REM inlays in articulation with ceramic heads demonstrated stable gravimetric wear rates for up to 4 weeks of artificial ageing, and after 5 weeks a slight increase from 2.0 ± 0.3 mg per million cycles for REMvirgin delta to 3.4 ± 0.7 mg per million cycles for REMaged5 delta was measured ($p = 0.0353$). After 6 weeks of artificial ageing, a relatively high gravimetric wear rate of 52.0 ± 16.4 mg per million cycles was calculated for REMaged6 delta, a 26-fold increase compared to the REMvirgin delta conditions ($p = 0.00621$), indicating structural material degradation of the XLPE remelted inlays (Fig. 3). The VitE inlays showed similar wear behaviour without any statistical difference, independently of the time of artificial ageing (up to 6 weeks), with gravimetric wear rates in articulation against ceramic heads of 2.5 ± 0.5 mg per million cycles for VitEvirgin delta of 1.7 ± 0.6 mg per million cycles for VitEaged2 delta ($p = 0.194$), of 2.3 ± 0.1 mg per million cycles for VitEaged4 delta ($p = 0.533$) and of 2.3 ± 0.7 mg per million cycles for VitEaged6 delta ($p = 0.857$).

In articulation with 36 mm ceramic heads, cumulative gravimetric wear of STD inlays significantly increased from 106.4 ± 4.7 mg for STDvirgin forte to 170.8 ± 21.5 mg for STDaged2 forte ($p = 0.007189$) and to 365.8 ± 37.2 mg for STDaged4 forte ($p = 0.000391$) (Fig. 4). For the REM inlays, statistical analysis demonstrated a significant (2.5-fold) increase in cumulative wear of 27.7 ± 3.8 mg for REMaged5 delta compared to 11.3 ± 1.3 mg for REMvirgin delta ($p = 0.001957$) and a 10-fold increase to 278.1 ± 72.7 mg for REMaged6 delta compared to REMaged5 delta ($p = 0.003985$), respectively. The cumulative gravimetric wear of the VitE inlays remained on a constant level, with 14.9 ± 3.1 mg for VitEvirgin delta, 10.7 ± 2.2 mg for VitEaged2 delta ($p = 0.132$), 12.1 ± 1.4 mg for VitEaged4 delta ($p = 0.226$) and 12.5 ± 3.2 mg for VitEaged6 delta ($p = 0.411$), independently of the time of artificial ageing.

After 5 million cycles, the cumulative geometric head penetration of STD inlays increased from 130 µm for STDvirgin forte to 230 µm for STDaged4 forte (the test group was terminated after 1 million cycles due to structural material fatigue of the inserts). For the REM inlays, cumulative geometric head penetration demonstrated...
a substantial increase from 70 μm for REMaged2 delta compared to 480 μm for REMaged6 delta after 5 million cycles in articulation with 36 mm ceramic heads. The cumulative geometric head penetration of the VitE inlays remained on a relatively constant level with 70 μm for VitEaged2 delta and 90 μm for VitEaged6 delta (Fig. 5).

For the REM inlays subjected to wear simulation under conditions of third-body particulate debris, the gravimetric wear rates were 5.9 ± 0.6 mg per million cycles in articulation with BIONOX5 delta (REMthird-body BIONOX5) and 35.8 ± 11.6 mg per million cycles in articulation with CoCrMo (REMthird-body CoCrMo), compared to clean conditions with 2.5 ± 0.5 mg per million cycles for REMvirgin delta and 3.4 ± 0.5 mg per million cycles for REMvirgin CoCrMo (Fig. 6). The REM inlays in articulation with ceramic heads showed a 2.95-fold increase in wear rate and those in articulation with CoCrMo heads a 10.5-fold increase, with a statistically significant difference of p = 0.00048.

For the VitE inlays subjected to wear simulation under conditions of third-body particulate debris, the gravimetric wear rates were 2.6 ± 1.6 mg per million cycles in articulation with BIONOX5 delta (VitEthird-body BIONOX5) and 23.5 ± 15.5 mg per million cycles in articulation with CoCrMo (VitEthird-body CoCrMo), compared to clean conditions with 2.5 ± 0.5 mg per million cycles for VitEvirgin delta and 3.4 ± 0.5 mg per million cycles for VitEvirgin CoCrMo. No substantial was measured for the VitE inlays in articulation with ceramic heads (p = 0.876) or in articulation with CoCrMo heads, a 6.9-fold increase in wear rate (p = 0.0875).

The cumulative weight loss of the ceramic and cobalt–chromium heads subjected to wear simulation under conditions of third-body particulate debris was 0.11 ± 0.11 mg for BIONOX5 delta and 11.92 ± 4.01 mg for CoCrMo, compared to clean conditions (standard ISO) with 0.15 ± 0.12 mg for BIONOX5 delta and 0.39 ± 0.20 mg for CoCrMo (Fig. 7). For the articulating ceramic heads, no substantial change was measured (p = 0.507), and for the CoCrMo heads articulating under third-body conditions there was a 30.6-fold increase in cumulative head wear, which was a statistically significant difference (p = 0.000036).

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**Fig. 2.** Oxidation index vs. time of artificial ageing for STD, REM and VitE polyethylene inlays prior to wear testing. The oxidation index was calculated as the arithmetic mean of the measured oxidation index at the articulating surface and at depths of 100, 200, 300, 400, 500 and 1000 μm.

**Fig. 3.** Gravimetric wear rates vs. time of artificial ageing for STD, REM and VitE polyethylene inlays in articulation with cobalt–chromium and ceramic heads. Note: the testing of the STDaged forte group was terminated after 1 million cycles due to structural material fatigue of the inserts. Based on that, the wear rate for STDaged forte was calculated from the cumulative wear after 1 million cycles.
5. Discussion

The objective of our study was to evaluate the influence of prolonged artificial ageing on oxidation resistance and subsequent wear behaviour of vitamin E-stabilized in comparison to standard and highly cross-linked, remelted polyethylene, and the degradation effect of third-body particles on XLPE inlays in total hip arthroplasty.

In terms of wear and osteolysis outcomes, systematic reviews of the clinical performance have highlighted the evident benefits of highly cross-linked polyethylenes in total hip arthroplasty in mid-term follow-ups [11,15,16]. In our hip simulator study on 36 mm cobalt–chromium and ceramic heads articulating with different polyethylene inlay materials the mean gravimetric wear rates ranged from 19.0 mg per million cycles for STD, from 2.0 to 3.4 for REM and from 2.5 to 3.4 for VitE in a virgin, and from 30.3 to 365.8 for STD, from 1.0 to 51.9 for REM and from 1.7 to 3.4 for VitE under artificially aged (2, 4, 5 or 6 weeks) conditions. In spite of some limitations, such as applied load profile, kinematics, head size and lubricant, our in vitro findings for virgin conditions fall within the range of wear data reported in the literature for standard, XLPE remelted and XLPE vitamin E-stabilized polyethylene acetabular liners (Table 2).

To the best of our knowledge, this is the first study to analyse the influence of oxidation on the wear behaviour of remelted XLPE and vitamin E-stabilized XLPE hip articulations. Using a tri-pin-on-disc tribometer, Besong et al. [37] studied the effect on wear of 10 years of shelf storage after γ-irradiation in air. Sliding against a stainless steel counterface, the shelved material produced 6-fold more volumetric wear compared to the non-irradiated material. Analysing the effect of sterilization method on the wear resistance of acetabular cups (vs. 28 mm CoCrMo heads) in a hip joint simulator, McKellop et al. [38] demonstrated that cross-linking by γ-irradiation and low-oxygen packaging improves wear resistance substantially vs. a non-irradiated control. Under steady-state conditions for the γ-irradiated acetabular cups sterilized in an inert gas atmosphere, they reported a mean wear rate of 16.6 mg per million cycles, 50% lower than the non-irradiated controls with a mean wear rate of 38.4 mg per million cycles [38]. After 30 days of accelerated ageing (80 °C in air), the γ-irradiated cups wore by 57.3 mg per million cycles, twice the amount of non-irradiated controls, at 33.9 mg per million cycles. McKellop et al. concluded that long-term oxidation of the residual free radicals may markedly reduce wear resistance due to oxidative degradation of the material.

Oxidative degradation of polyethylene components for total joint arthroplasty is mainly initiated by high-energy gamma or electron beam irradiation applied during cross-linking or sterilization of implants [12,24,39].

More than a decade ago, gamma sterilization in air and shelf storage before implantation were identified as parameters responsible for poor long-term clinical performance in hip and knee arthroplasty patients [40,41]. In addition, there is evidence that further oxidation and polymer degradation take place in vivo not only in hip inlays γ-sterilized in air or in an inert gas atmosphere, but also in highly cross-linked polyethylene components annealed after irradiation [20,21,42]. The in vivo degradation of polyethylene may be due to cyclic fatigue loading, as mechanical stress can break polymer chains, release free radicals and permit absorption of liquids, allowing oxygen to penetrate into the material by diffusion and influence the material integrity by oxidation [12,27,43,44]. Kurtz et al. [21] demonstrated that the in vivo oxidative degradation of standard (γ inert) and highly cross-linked (XLPE annealed) polyethylene liners may cause long-term failure modes to a significant extent.

Post-irradiation melting of highly cross-linked components lowers the concentration of residual free radicals to undetectable levels and prevents mid-term oxidation [8,16], but it leads to a loss of crystallinity and reduces the mechanical properties (fatigue and impact strength) [16,23,45,46]. To improve resistance against oxidation and fatigue crack propagation, vitamin E is surface diffused and influence the material integrity by oxidation [12,27,43,44]. Kurtz et al. [21] demonstrated that the in vivo oxidative degradation of standard (γ inert) and highly cross-linked (XLPE annealed) polyethylene liners may cause long-term failure modes to a significant extent.

Using a bidirectional pin-on-disc set-up, Oral et al. [22] found an increased wear rate of 18 mg per million cycles in conventional polyethylene γ-irradiated in nitrogen (25 kGy) after moderate ageing (80 °C in air, 5 weeks), vs. 13 mg per million cycles in an unaged condition, but found wear rates of 1.1 and 1.9 mg per million cycles without any change in remelted XLPE (100 kGy) and XLPE stabilized by vitamin E diffusion (92 kGy) after accelerated ageing.

In basic experiments on non-irradiated polyethylene (GUR 1050) in the virgin condition vs. a specimen containing vitamin
Fig. 5. Three-dimensional geometric changes in the direction vertical to the transversal plane for STD, REM and ViE polyethylene inlays at the bearing interface after 5 million cycles in articulation with ceramic heads: loaded soak control specimen (top) and representative specimen under wear simulation after 0, 2, 4, 5 and 6 weeks of artificial ageing. Scale: red = +0.05 mm and purple = −0.3 mm. Note: the testing of the STD_aged Forte group was terminated after 1 million cycles due to structural material fatigue of the inserts.
E. Bladen et al. [48] found no significant differences in regard to wear rates and particle size distribution, but did find a substantially decreased inflammatory potential of the polyethylene particulate debris containing vitamin E.

For highly cross-linked polyethylene blended with vitamin E, Affatato et al. [49] reported a higher wear rate compared to irradiated and annealed XLPE with the same dose level of 70 kGy, which they contended was due to the vitamin E reducing the cross-linking efficiency [50]. They described a correlation between the cross-link density and the wear resistance of the polyethylene.

In the current in vitro study, the polyethylene inlays for STD, REM and VitE were artificially aged for 2, 4, 5 and 6 weeks and oxidation index measurements were performed by FTIR to determine the appropriate oxidation grade prior to the wear simulation. The oxidation index after ageing ranged from 0.67 to 4.48 for STD, from 0.034 to 0.473 for REM and from 0.046 to 0.048 for VitE, which is in good accordance with clinically prevalent oxidation grades [51].

In 16 standard polyethylene acetabular liners revised after an average of 11.5 years (range 8.9–13.5 years), Kurtz et al. [52] recorded oxidation index values of 2.11 ± 1.13 (range 0.43–4.57) on unworn surfaces and 1.21 ± 0.77 (range 0.3–3.27) on worn surfaces. In another study, Schwiesau et al. [53] found the mean oxidation grade of 59 standard polyethylene acetabular liners retrieved after an average of 11.7 years (range 0.15–28 years) to be 1.83 (range 0.48–3.87) in the hip articulation and 1.1 (range 0.13–2.84) in the rim area.

Kurtz et al. [21] provide evidence that oxidative degradation of irradiated polyethylene occurs in vivo on acetabular liners sterilized in air, but also on components γ-sterilized in inert atmosphere and on annealed highly cross-linked polyethylene components. For hip inserts γ-sterilized in air (n = 19) with a shelf life of 0.3 years and a mean implantation time of 11.1 years (range 5.9 to 16.8), they measured a mean oxidation index of approximately 4.9 in the rim area and of 1.2 on the bearing surface [21]. In annealed
Table 2
Overview of wear rates on hip articulations with different polyethylene inlay materials from a clinical study and a series of in vitro wear simulations.

| Authors | Study Design | Patients Follow-up | Inlay Material | Oxidation Index | Ra (μm) 1/cm 1
<table>
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<tr>
<td>Triclot et al. [33]</td>
<td>Prospective, randomized, in vivo (n = 102)</td>
<td>15 years</td>
<td>CoCrMo</td>
<td>PEstd. γ in N2 25–40 kGy</td>
<td>58 μm year −1 (forte)</td>
</tr>
<tr>
<td>Muratoglu et al. [7]</td>
<td>In vitro</td>
<td>20 million cycles</td>
<td>CoCrMo</td>
<td>PEstd. γ in air 25–40 kGy</td>
<td>102 μm year −1 (CoCr)</td>
</tr>
<tr>
<td>Mc Kellop et al. [6]</td>
<td>In vitro</td>
<td>Various radiation dosehip simulator</td>
<td>CoCrMo</td>
<td>PEstd. γ in air remelt.</td>
<td>107 μm year −1 (forte)</td>
</tr>
<tr>
<td>Fisher et al. [34]</td>
<td>In vitro</td>
<td>Hip simulator 2–7 mc (steady state)</td>
<td>CoCrMo &amp; BIOLOX forte</td>
<td>PEstd. γ in N2 25–40 kGy</td>
<td>190 μm year −1 (CoCr)</td>
</tr>
<tr>
<td>Johnson et al. [35]</td>
<td>In vitro</td>
<td>Varying inlay thickness hip simulator</td>
<td>CoCrMo</td>
<td>PEstd. γ in argon 25 kGy</td>
<td>138 μm year −1 (7 to 10 a)</td>
</tr>
<tr>
<td>Oral et al. [36]</td>
<td>In vitro</td>
<td>XLPE inlays doped with vitamin E hip simulator</td>
<td>CoCrMo</td>
<td>PEstd. γ in air 25–40 kGy</td>
<td>142 μm year −1 (7 to 10 a)</td>
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Table 3
Overview of geometric head penetration rates on hip articulations with different polyethylene inlay materials from a series of clinical studies with ceramic and cobalt–chromium heads.

| Authors | Study Design | Patients Follow-up | Inlay Material | Oxidation Index | Ra (μm) 1/cm 1
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<tr>
<td>Descamps [57]</td>
<td>In vivo</td>
<td>15 years</td>
<td>CoCrMo &amp; BIOLOX forte</td>
<td>PEstd. γ in air 25–40 kGy</td>
<td>58 μm year −1 (forte)</td>
</tr>
<tr>
<td>Ihle et al. [58]</td>
<td>In vivo</td>
<td>20 years</td>
<td>CoCrMo &amp; BIOLOX forte</td>
<td>PEstd. γ in air 25–40 kGy</td>
<td>102 μm year −1 (CoCr)</td>
</tr>
<tr>
<td>Bragon et al. [13]</td>
<td>In vivo (eliminated creep)</td>
<td>26 &amp; 28</td>
<td>CoCrMo &amp; BIOLOX forte</td>
<td>PEstd. γ in air 25–40 kGy</td>
<td>142 μm year −1 (7 to 10 a)</td>
</tr>
<tr>
<td>Geerdink et al. [59]</td>
<td>In vivo (prospect. randomized)</td>
<td>8 years</td>
<td>CoCrMo</td>
<td>PEstd. γ in air 25–40 kGy</td>
<td>190 μm year −1 (CoCr)</td>
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<td>Reynolds et al. [60]</td>
<td>In vivo</td>
<td>9 years</td>
<td>CoCrMo</td>
<td>PEstd. γ in N2 25–40 kGy</td>
<td>138 μm year −1 (7 to 10 a)</td>
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<td>Mutimer et al. [61]</td>
<td>In vivo (prospect. randomized)</td>
<td>5.5 years</td>
<td>CoCrMo</td>
<td>PEstd. γ in N2 25–40 kGy</td>
<td>142 μm year −1 (7 to 10 a)</td>
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<td>Lee et al. [62]</td>
<td>In vivo</td>
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<td>CoCrMo</td>
<td>PEstd. γ in N2 25–40 kGy</td>
<td>190 μm year −1 (CoCr)</td>
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highly cross-linked liners (n = 21) with an average shelf life of 0.3 years and an average implantation time of 3 years (range 0.02 to 6), they detected a mean maximum oxidation index of 3.3 in the rim area and 0.7 on the bearing surface [21]. Based on these findings, they concluded that oxidative degradation in vivo has to be considered as a potential long-lasting failure mode for polyethylene acetabular liners.

Collier et al. [19] evaluated five different highly cross-linked polyethylenes under accelerated ageing conditions (pure oxygen, +63 °C, 3 atm) for 28 days and found a substantial increase in the oxidation index, from 0.04 (as received) to 0.3 (28 days ageing), on a highly cross-linked and annealed material, but no difference on the remelted highly cross-linked material. Since oxidation is governed by diffusion, the conditions of Collier et al. [19] are not able to produce the same oxidative effect as the ageing conditions according to ASTM F2003-02 (+70 °C, 5.79 atm, 14–42 days) applied in the current study.

Currier et al. [42] found that retrieved barrier-packed polyethylene bearings γ-irradiated in air and in inert gas exhibit oxidation grades substantially higher than shelf-stored controls, clearly demonstrating that progressive oxidation is caused by the in vivo environment. According to them, an oxidation level of 1–1.5 represents a threshold for a substantial loss in mechanical properties that follows an exponential function with time [42].

For short- to mid-term implantation times, Wannomae et al. [20] found a mean oxidation index of 1.2 (range 0.22–5.8) in irradiated and annealed highly cross-linked liners after 4–33 months, but no increase in remelted highly cross-linked liners (range 0.02–0.11) serving from 1 to 36 months in vivo. To prevent long-term oxidation, increase in crystallinity and embrittlement of polyethylene implants, they recommend the stabilization of residual free radicals by remelting after irradiation [20]. Carpentieri et al. [28] demonstrated that the degree of crystallinity is an important factor for post-irradiation oxidative degradation of polyethylene, a possible explanation for the exponential nature of the oxidation process.

Kurtz [54] described a mechanism of in vivo oxidation driven by molecular oxygen dissolved in synovial fluids which, despite its...
low partial pressure, was able to substantially oxidatively degrade irradiated polyethylene in the long term. He considered dissolved molecular oxygen to be a driving force of progressive oxidation reactions in vivo, in particular if the polymer contained already unstabilized free radicals [54]. Based on a retrieval analysis, he predicted an oxidation index of >1 after 10 years’ implantation of polyethylene components γ-sterilized and packed in inert atmosphere.

Muratoglu et al. [27] first described the ex vivo stability loss of irradiated and remelted highly cross-linked polyethylene by the absorption of lipids from the synovial fluid, which can generate new free radicals in the material and initiate progressive oxidation and degradation. Their findings suggest that, under specific conditions, an oxidatively stable, irradiated and remelted highly cross-linked polyethylene can become unstable during short-term implantation [27]. This points to a possible limitation of our study: the accelerated oxidation by pure oxygen, pressure and temperature may not be an appropriate method for the artificial ageing of remelted XLPE [55]. In the absence of another working in vitro set-up for accelerated ageing based on synovial fluid or lipids [27,54], the decision was to use a standardized set-up (ASTM F2003-02) for the creation of oxidative degradation in the STD, REM and VitE test groups. Furthermore, Currier et al. [51] found a maximum oxidation index of 0.36 in retrieved highly cross-linked (65 kGy, e-beam) and remelted tibial inserts after 3.3 years in vivo, which corresponds well to the oxidation index of 0.14 after 5 weeks and of 0.47 after 6 weeks of artificial ageing in our study. They calculated an average articular oxidation rate of 0.07 per year, which means that the oxidation grades of the XLPE remelted hip inlays in our study after prolonged artificial ageing reflect an estimated time in vivo of between 2 and 7 years [51].

In our hip simulator study on 36 mm cobalt–chromium and ceramic heads articulating with different polyethylene inlay materials after 2, 4, 5 and 6 weeks of artificial ageing, the mean geometric head penetration was measured after 5 million cycles in vitro. Based on an average of 1.76 million gait cycles per year for hip and knee arthroplasty patients [56], the annual head penetration ranged from 46 to 405 μm year−1 for STD, from 25 to 169 μm year−1 for REM and from 25 to 32 μm year−1 for VitE in articulation with ceramic heads, and from 25 to 170 μm year−1 for REM and from 25 to 32 μm year−1 for VitE in articulation with cobalt–chromium heads. Our in vitro findings fall within the range of geometric head penetration data for polyethylene acetabular liners reported in the literature (Table 3).

In the literature, there is little data on third-body wear resistance of hip inlays made out of highly cross-linked polyethylene [12,63,64]. To fill this gap, we also evaluated the degradation effect of third-body bone cement particles on REM and VitE hip inlays in articulation with cobalt–chromium and ceramic heads. Wang et al. [64] examined the wear behaviour of XLPE inlays (75 kGy annealed) articulating against CoCrMo and alumina ceramic heads in a 32 mm diameter bearing combination in the presence of third-body particulate debris. They used particles of PMMA bone cement with a mean size of 150 μm and a concentration of 5 g l−1. In our study, we generated the third-body debris out of Palacos® R bone cement containing zirconium dioxide as a radiopaque material and used the same particle concentration and a similar size (125–150 μm). We tested a femoral head size of 36 mm diameter under third-body conditions and found a mean wear rate of 35.8 mg per million cycles on the CoCrMo/REM combination, similar to that of Wang et al. [64], with 110 mg per million cycles. For the combination of alumina ceramic (BIOLOX® forte) and XLPE, they reported a mean wear rate of 32.6 mg per million cycles.

In contrast, we measured a wear rate of 5.9 mg per million cycles for REM inlays articulating against BIOLOX® delta heads (Ø 36 mm) in the presence of bone cement particulate debris, amounting to only 18% of the wear rate found by Wang et al. [64]. A possible explanation may be the higher resistance of BIOLOX® delta ceramic heads compared to BIOLOX® forte against scratching and abrasive wear initiated by the zirconia dioxide radiopaque material in the bone cement debris. This hypothesis is supported by Stewart et al. [65] and Kuntz et al. [66], who found a substantially higher resistance of zirconia-toughened alumina ceramic (BIOLOX® delta) self-mating articulations compared to alumina ceramic (BIOLOX® forte) bearings under microseparation wear testing conditions.

6. Conclusion

From our observations, we conclude that, after 2 weeks of artificial ageing, standard polyethylene shows substantially increased wear due to oxidative degradation, whereas highly cross-linked remelted polyethylene has a higher oxidation resistance. However, after 5 weeks of enhanced artificial ageing, remelted XLPE also starts to oxidate, in correlation with increased wear.

Vitamin E-stabilized polyethylene is effective in preventing oxidation after irradiation cross-linking even under prolonged artificial ageing up to 6 weeks, resulting in a constantly favourable hip wear behaviour.

Declarations

Competing interests: T.G., M.H., M.M., R.S. and W.B. are employees of Aesculap, Tuttingen, a manufacturer of orthopaedic implants. M.J. is an advising surgeon of Aesculap. S.U. was receiving research funding in correlation with Aesculap R&D projects.

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Ethical approval

Not required.

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Appendix A. Figures with essential colour discrimination

Certain figures in this article, particularly Figs. 1–7 are difficult to interpret in black and white. The full colour images can be found in the online version, at http://dx.doi.org/10.1016/j.actbio.2014.02.052.

References


