History and Systematic Review of Wear and Osteolysis Outcomes for First-generation Highly Crosslinked Polyethylene

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Abstract

Background Highly crosslinked polyethylene (HXLPE) was introduced to reduce wear and osteolysis in total joint arthroplasty. While many studies report wear and osteolysis associated with HXLPE, analytical techniques, clinical study design and followup, HXLPE formulation and implant design characteristics, and patient populations differ substantially among investigations, complicating a unified perspective.

Questions/purposes Literature on first-generation HXLPE was summarized. We systematically reviewed the radiographic wear data and incidence of osteolysis for HXLPE in hip and knee arthroplasty.

Methods PubMed identified 391 studies; 28 met inclusion criteria for a weighted-averages analysis of two-dimensional femoral head penetration rates. To determine the incidence of osteolysis, we estimated a pooled odds ratio using a random-effects model.

Results Weighted-averages analyses of femoral head penetration rates in HXLPE liners and conventional UHMWPE liners resulted, respectively, in a mean two-dimensional linear penetration rate of 0.042 mm/year based on 28 studies ($n = 1503$ hips) and 0.137 mm/year based on 18 studies ($n = 695$ hips). The pooled odds ratio for the risk of osteolysis in HXLPE versus conventional liners was 0.13 (95% confidence interval, 0.06–0.27) among studies with minimum 5-year followup. We identified two clinical studies of HXLPE in TKA, preventing systematic analysis of outcomes.

Conclusions HXLPE liner studies consistently report lower femoral head penetration and an 87% lower risk of osteolysis. Reduction in femoral head penetration or osteolysis risk is not established for large-diameter (> 32 mm) metallic femoral heads or ceramic femoral heads of any size. Few studies document the clinical performance of HXLPE in knees.

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Introduction

Ultrahigh-molecular-weight polyethylene, also known as UHMWPE, polyethylene, or simply “poly,” has been an orthopaedic bearing material for total joint arthroplasties since the 1960s [26]. Polyethylene is chemically and conceptually simple, produced by the polymerization of ethylene gas into a macromolecular carbon chain with pendant hydrogen atoms, yet the polyethylene biomaterials in clinical use today, whether crosslinked by gamma or electron beam radiation and annealed or remelted by thermal treatments, are exceedingly more complex than the gamma-air-sterilized polyethylene used up to the 1990s. Even today, the state of knowledge for polyethylene

biomaterials continues to evolve, and the number of clinical studies related to polyethylene has increased substantially within the past 5 years.

Not only the polyethylene biomaterials themselves but their clinical applications have expanded since the 1990s. Within the United States, the most widely used clinical application of polyethylene biomaterials today is in knee arthroplasty. For the hip, on the other hand, polyethylene biomaterials are still used in the majority of cases, but hard-on-hard alternatives, including metal-on-metal and ceramic-on-ceramic, have emerged as potential alternatives for younger, higher-demand patients. Thus, polyethylene biomaterials remain the material of choice for knee arthroplasty; however, considerable debate continues regarding the selection of alternative bearings for the hip.

Highly crosslinked and thermally treated polyethylenes (HXLPEs) were clinically introduced starting in 1998 to reduce wear and the incidence of revision resulting from osteolysis. A second motivation for developing these polyethylenes was to reduce oxidation, which had been associated with short-term clinical failures after gamma sterilization in air and long-term shelf aging in air. However, the strategies for achieving wear reduction and oxidation resistance varied among orthopaedic implant producers. One approach, known as annealing, involved a single thermal treatment below the crystalline melt transition in polyethylene to preserve crystallinity and mechanical properties [79]. When combined with terminal gamma sterilization in an inert environment, this strategy resulted in a material containing elevated residual free radicals with the potential to oxidize in vivo. A second approach to polyethylene formulation, referred to as remelting, involved thermal treatment above the melt transition [95, 103]. This second strategy resulted in a material with undetectable free radicals but at the expense of reduced crystallinity and lower material properties.

Systematic reviews of outcomes involving HXLPEs are rare [102]. Mu et al. [102] performed a systematic review of radiographic outcomes for HXLPE in hip arthroplasty, but the review only included the findings of eight prospective randomized studies. Our present study is composed of four parts, each addressing one of the following questions: (1) What is the historical context for first-generation HXLPEs used in hip and knee arthroplasty? (2) How do study factors (eg, followup, radiographic wear methodology) and implant design factors (eg, HXLPE formulation, head size, head material) influence radiographic wear outcomes for the hip? (3) How do implant design factors influence radiographic osteolysis outcomes in the hip? (4) How do implant design factors influence radiographic outcomes in the knee?

Search Strategy and Criteria

The history and development of polyethylene biomaterials for orthopaedics spans five decades and is recorded in research and review articles, conference proceedings, and several books [34, 74, 76, 77, 139]. A MEDLINE search was considered impractical to summarize in a concise review and would also neglect the historical contributions of key abstracts at national conferences that were never published in journal articles. Instead, the references for the first part of this review were drawn from the bibliographies of the *UHMWPE Biomaterials Handbook* [76], which is a comprehensive monograph on the history of this subject.

To answer the remaining research questions for this review, an advanced PubMed search was performed of the hip and knee arthroplasty literature. Title and abstract fields were queried using the following precise syntax: (((("Aeonian"[Title/Abstract] OR "Crossfire"[Title/Abstract] OR "Marathon"[Title/Abstract] OR "XLPE"[Title/Abstract] OR "Longevity"[Title/Abstract] OR "Durasul"[Title/Abstract] OR "Prolong"[Title/Abstract]) AND (polyethylene[Title/Abstract] OR UHMWPE[Title/Abstract] OR UHMW*PE[Title/Abstract])) OR ((("Aeonian"[Title/Abstract] OR "Crossfire"[Title/Abstract] OR "Marathon"[Title/Abstract] OR "XLPE"[Title/Abstract] OR "Longevity"[Title/Abstract] OR "Durasul"[Title/Abstract] OR "Prolong"[Title/Abstract]) AND (hip OR knee)) OR ((cross*link*[Title/Abstract] OR cross-link*[Title/Abstract]) AND (polyethylene[Title/Abstract] OR UHMWPE[Title/Abstract] OR UHMW*PE[Title/Abstract]))) AND (wear OR osteolysis OR penetration)) AND "2001/1/1"[Publication Date] : "3000"[Publication Date] AND "0"[Publication Date] : "3000"[Publication Date]) AND English[Language]. These search terms were chosen based on the brand names of the first-generation, HXLPEs introduced for total joint arthroplasty starting in 1998 (Table 1). For the purposes of this review, second-generation crosslinked polyethylenes, fabricated by mechanical annealing [80], sequential annealing [43], and diffusion of vitamin E [112], were excluded because of their recent introduction and the absence of a body of published journal studies documenting their clinical performance, warranting a systematic review. The search also included terms for crosslinked and polyethylene or UHMWPE. The search was also narrowed to identify wear or osteolysis or penetration studies published in English. Using these criteria, 391 articles published after January 1, 2001, were obtained on September 11, 2010.

By reviewing titles and abstracts, duplicates were excluded, as well as studies with less than 2 years of radiographic followup for either wear or osteolysis, resulting in 44 articles for the hip and two articles for the knee (Fig. 1) for detailed evaluation for systematic review

Table 1. Factors considered in the systematic review of 2D linear penetration rate and osteolysis of conventional and HXLPE in hips

Factor	Categories
Mean patient age	≤ 60 years old > 60 years old
Mean patient bone mass index	≤ 25 kg/m ² > 25 kg/m ²
HXLPE formulation	Aeonian Crossfire Durasul Longevity Marathon XLPE
Femoral head size	Small (≤ 28 mm) Large (> 28 mm)
Femoral head material	Metal Ceramic
2D linear cup penetration rate determination method	Martell Other
Study type	Randomized controlled trial Cohort trial
Followup period	≤ 5 years > 5 years

2D = two-dimensional; HXLPE = highly crosslinked polyethylene.

Fig. 1 The review was performed systematically and included a detailed analysis of 44 hip articles and two knee articles.

and evaluation of inclusion and exclusion criteria for the weighted-averages analysis.

Two reviewers (JDP, HAG) extracted information from 44 hip studies independently using a standardized extraction form. Information extracted included study design, number of patients, patient demographic information (age, gender, weight, body mass index), followup time, device design factors (acetabular liner material, femoral head size, femoral head material), patient diagnoses, and radiographic

wear outcome measures (polyethylene two-dimensional [2D] total linear penetration rates, methodology for femoral head penetration assessment, incidence of osteolysis). Extracted data were compared, and in the case of disagreements, original data were rechecked by both investigators and resolved by discussion and consensus with the first author (SMK). All the data extracted from these 44 hip studies can be found in Appendix 1 (supplemental materials are available with the online version of CORR). The data for the two knee studies were sufficiently different from the hip results that we summarized them independently later in this review.

By inspecting the extracted data, we determined sufficient information was available to compare femoral head penetration and osteolysis outcomes among a subset of the reported THA studies. Specifically, 2D linear penetration rates were pooled from randomized controlled trials (RCTs) and prospective and retrospective cohort studies with comparable outcome measures to conduct a weighted-averages analysis using a random-effects model in the Comprehensive Meta-analysis™ Version 2.2 software (Biostat, Englewood, NJ). The 28 studies included in the weighted averages comprised nine RCTs and 19 observational cohort studies.

Studies reporting duplicate trial data or lacking comparable outcome assessment were excluded from the weighted-averages analysis. Five studies were excluded based on clinical assessments of only a bedding-in rate or a steady-state wear rate. We identified one cohort study directly comparing femoral penetration among different HXLPE formulations [137], but this study was excluded from our weighted-averages analysis because it only reported steady-state penetration rates. Similarly, Calvert et al. [22] excluded the bedding-in penetration rate and reported only the mean steady-state radiographic penetration rates from 6 months to 4 years. Another study excluded from the weighted-averages analysis was by Fukui et al. [45], which did not separate out radiographic outcomes by HXLPE formulation, implying the femoral head penetration behavior was similar between the two groups. Other studies excluded from the analysis included Miyanishi et al. [100], Ayers et al. [5], McCalden et al. [92], Garcia-Rey et al. [46], Bragdon et al. [20], Digas et al. [38], Geller et al. [49], and Mutimer et al. [104] because they lacked comparable clinical outcome measures. Glyn-Jones et al. [51], Heisel et al. [60], Rohrl et al. [121], and Digas et al. [39] were all cases of multiple publications on the same study. Only the most recent study [58] was included in the analysis because it contained the data from the earlier cohort.

Further analysis was conducted to determine whether device design (femoral head material, femoral head size, HXLPE formulation) or study design factors (study type,

methodology to assess wear, followup time) influenced reported radiographic penetration rates. The continuous data for each of the factors listed were converted to dichotomous categorical data (Table 1). Additional subgroup analysis evaluated the standardized difference in means (Hedge's *g* statistic) of 2D linear penetration rates in RCTs and cohort studies between the UHMWPE and HXLPE groups using a random-effects model. A subgroup analysis was also conducted to determine whether patient factors, device design factors, or study factors influenced the standardized difference in means.

For analysis of the incidence of osteolysis in patients with conventional and HXPLE liners, observational cohort studies and RCT studies were combined and the pooled odds ratio was estimated using a random-effects model. Only studies with an average followup of at least 5 years were considered. A subgroup analysis was also conducted to determine whether patient factors, device design factors, or study factors influenced the pooled odds ratio for osteolysis.

History and Development of HXLPE

A full recounting of the historical events leading up to the "discovery" of polyethylene for hip arthroplasty in 1962 by Sir John Charnley and his engineering associate, Harry Craven, can be found in Charnley's monograph [27] and biography [135], but it is instructive to briefly recall UHMWPE arrived in orthopaedics by chance rather than by design. Indeed, polyethylene was not Charnley's first, or even his second, choice as a bearing material for his low-friction arthroplasty [25, 26]. It was not until after the catastrophic clinical failure of polytetrafluoroethylene (PTFE) that Charnley sought bearing material alternatives, and his initial choices were glass-filled variants of PTFE [27]. Were it not for the curiosity of Harry Craven, a technician working for Charnley at the time, UHMWPE would not have been wear tested [135]. When Charnley saw the superior wear performance of polyethylene compared with PTFE, he tested particles in his own thigh before allowing its use as a bearing material for joint arthroplasty [26].

Charnley can be credited not only with the low-friction design principle for hip arthroplasty incorporating polyethylene [27] but also with recommending the use of gamma sterilization for polyethylene components [28]. Gamma radiation continues to be an effective and convenient method for sterilizing joint arthroplasty materials [65], including polyethylene [75]. Charnley personally advocated gamma sterilization because it was the method used for the implants in his hospital [28]. Charnley saw little benefit to alternative sterilization methods, and

he expressed these opinions forcefully in his personal correspondence [28].

Charnley's advocacy of gamma radiation sterilization would later prove to be a double-edged sword. On the one hand, the crosslinking imparted by a single sterilization dose (25–40 kGy) of gamma radiation substantially improved its wear resistance [29, 55] and contributed to the long-term clinical success of the metal-on-polyethylene wear couple used in hip and knee arthroplasty to this day. Gamma sterilization in the presence of air also had a drawback in that it rendered the polymer vulnerable to oxidation before implantation [81, 113] and during in vivo exposure [30, 36, 78, 82, 129]. It would take decades, however, for gamma sterilization in air to be challenged as the industry standard for polyethylene, because the deleterious effects of oxidation in polyethylene take many years to manifest [81].

Orthopaedic bearing designs incorporating gamma-air-sterilized polyethylene proved to be more robust and reliable than other early alternatives, including first-generation metal-on-metal of the 1960s [4, 94, 120] and ceramic-on-ceramic bearings of the 1970s [17]. Difficulty in controlling the tolerances of early metal-on-metal hips has been hypothesized to result in seizure of some metal bearings culminating in early loosening [72], whereas first-generation alumina components were prone to unacceptably high fracture rates [141]. Orthopaedic manufacturers clinically introduced carbon-fiber-reinforced UHMWPE (Poly IITM; Zimmer, Inc, Warsaw, IN) [1, 33, 143] and high-pressure crystallized UHMWPE (Hylamer[®]; DePuy Orthopaedics, Inc, Warsaw, IN) [23, 86] in the 1970s and 1980s, respectively. Both of these attempts at polyethylene innovation also failed to win clinical acceptance due to short-term failures. In the case of Poly IITM, early failures were attributable to poor fiber-matrix adhesion and manufacturing reliability [33, 98]. In the case of Hylamer[®], oxidation after gamma sterilization in air proved to be the Achilles heel for this material [70, 125]. Thus, it was not that orthopaedic researchers were unable to innovate new bearing concepts after the introduction of polyethylene. Manufacturing and materials science before the 1990s proved insufficient to engineer orthopaedic bearings of greater reliability than metal-on-polyethylene.

During the 1990s, clinical concern about osteolysis and loosening of joint arthroplasties prompted a shift in the perception of polyethylene among orthopaedic researchers and surgeons [59, 67, 123, 138]. Polyethylene used in orthopaedics was subjected to greater scrutiny than ever before in terms of its manufacturing processes, sterilization techniques, wear mechanisms, and degradation chemistry. Research studies from this time period identified poor consolidation during manufacturing, wear, and poststerilization oxidation of polyethylene as key factors limiting the

longevity of total joint arthroplasties [81, 86, 113, 119, 145]. As a result, a number of improvements were implemented in the 1990s for the way medical-grade polyethylene was used in orthopaedics. These changes included improvements in the production of the resin or powder by no longer including calcium stearate [81, 96, 124, 130], manufacturing process optimization by compression molding and ram extrusion to eliminate consolidation defects [81, 86, 87, 115], and a shift away from gamma sterilization in air to either gas sterilization or gamma sterilization in a low-oxygen environment [16, 30, 31, 81, 96, 105, 113, 117, 118, 128, 129, 136]. In retrospect, among these advancements, the transition away from gamma sterilization in air was perhaps the most meaningful in terms of prevention of short-term oxidation-related failures observed in knee arthroplasty [32, 93].

The controversy surrounding polyethylene sterilization methods in the 1990s resulted in some manufacturers adopting gas sterilization by ethylene oxide or gas plasma [81, 117]. Although these implants effectively avoided the problems associated with oxidative degradation during shelf storage, the polyethylene was also not crosslinked by radiation [81]. As a result, comparative studies in hip simulator studies [96] and in radiographic wear studies showed higher wear rates for the uncrosslinked, gas-sterilized components when compared with gamma-sterilized controls, even after adjusting for poststerilization shelf life [63]. Because of its inferior wear resistance, the motivation to pursue uncrosslinked, gas-sterilized polyethylene for hip arthroplasty waned with the advent of HXLPE starting in the late 1990s.

In contrast, the use of gas-sterilized, uncrosslinked UHMWPE continues in TKA, because pitting, delamination, and fracture resistance were the dominant modes of concern for knee wear during the 1980s and 1990s [7–9, 15, 30, 136, 140, 142, 145]. In particular, several retrieval studies published in the 1990s showed ethylene oxide gas-sterilized knee implants effectively eliminated delamination when compared with gamma-sterilized components [30, 136, 140], and these retrieval observations were subsequently confirmed in vitro by wear studies [11, 116]. Furthermore, seminal work on the fatigue and fracture behavior of highly crosslinked and remelted UHMWPEs in the late 1990s raised questions about the suitability of these materials for knee arthroplasty as a result of the loss in mechanical properties with increasing doses of radiation [6, 7]. For these historical reasons, gas-sterilized, uncrosslinked tibial inserts remain in clinical use today as one of the options among gamma-inert sterilization and HXLPE knees.

Despite progress in understanding the reasons underlying wear and oxidation, dissatisfaction with polyethylene

performance was sufficient to encourage some members of the orthopaedic community to develop alternatives for hip arthroplasty [3, 14, 24, 40, 47, 107, 126]. Thus, orthopaedic manufacturers invested substantial resources in the commercialization of second-generation metal-on-metal [3, 24, 40] and ceramic-on-ceramic [14, 47, 107, 126] hip bearings during the 1990s, culminating in the growth in the adoption of these bearings at the start of the 21st century [18]. Concurrently, polyethylene researchers at multiple institutions around the world confirmed the finding that elevated doses of radiation crosslinking would reduce wear rates by an order of magnitude during in vitro hip simulator testing [95, 103, 133]. Clinical researchers in Japan and South Africa reported successful long-term case series initiated in the 1970s in which polyethylene had been exposed to elevated doses of gamma radiation [56, 109, 111] and silane chemistry [144]. Researchers also found thermal processing after radiation could influence the mechanical properties and oxidative resistance of the polymer [95, 103]. Taken together, these advances formed the basis for the first generation of radiation crosslinking and thermal stabilization technology and would usher in a renaissance of innovation for polyethylene biomaterials.

Starting in the late 1990s, the polyethylene research community turned its full attention to understanding and standardizing radiation crosslinking, whether by gamma radiation or electron beam irradiation, when combined with annealing and remelting thermal treatments [12, 53, 54, 68, 81, 84, 95, 97, 103, 134, 146]. In parallel with the expansion of scientific inquiry, the scope and number of international standards related to medical-grade UHMWPE increased. In 2003, the American Society for Testing and Materials (ASTM) convened a symposium dedicated to standardization of test methods related to highly crosslinked and thermally treated UHMWPE [77], and by 2006, members of the standards community had reached a consensus on a guide for characterizing the properties for this family of biomaterials [2]. Whereas medical-grade UHMWPE and its properties could be specified by one standard in the mid-1990s, 10 standards in ASTM have been published to date related to UHMWPE biomaterials.

In summary, most technical aspects of first-generation HXLPE production are now covered by international consensus standards, and these polyethylene biomaterials represent the current, clinical state of the art. Starting around 2005, a second generation of HXLPE was developed using alternative methods to stabilize the polymer [43, 80, 112]. These newer polyethylenes have not yet firmly established a long-term clinical track record and are beyond the scope of the present review. Next we turn to the radiographic outcomes of first-generation HXLPEs in the hip.

Systematic Review of Femoral Head Penetration Studies for HXLPEs in Hip Arthroplasty

The weighted-averages analysis of femoral head penetration rate in HXLPE liners resulted in a mean penetration rate of 0.042 mm/year (Fig. 2) based on 28 studies ($n = 1503$ hips). Among conventional UHMWPE liners, the pooled weighted average was 0.137 mm/year (Fig. 3) based on 18 studies ($n = 695$ hips). Comparing conventional UHMWPE and HXLPE using a random-effects model and illustrated by a forest plot (Fig. 4), available data support crosslinked polyethylene over conventional polyethylene.

Methodologic differences in the studies contributed substantially to the interstudy variability in femoral head penetration rates. We observed a difference in the weighted average of the total linear penetration rates of patients receiving HXLPE with a followup of 5 years or less (0.055 mm/year; 95% confidence interval [CI], 0.042–0.068) and greater than 5 years (0.034 mm/year; 95% CI, 0.025–0.042).

Additionally, the effect of the methodology (ie, Martell) was used to assess radiographic penetration on the overall penetration rates for conventional and HXLPE and calculated the weighted average as 0.036 mm/year (95% CI, 0.026–0.045) for Martell and 0.048 mm/year (95% CI, 0.039–0.058) for all the others. Among studies reporting results for conventional liners, the weighted-average linear penetration rate was calculated as 0.145 mm/year (95% CI, 0.100–0.191) and 0.125 mm/year (95% CI, 0.105–0.144) when radiographic penetration was assessed using the Martell methodology and other available methodology, respectively. These methodologic variations must be considered when interpreting the results of studies summarized by HXLPE formulation (Table 2).

The weighted-average mean 2D penetration rate for different HXLPE formulations ranged from 0.023 mm/year (Durasul) to 0.063 mm/year (Aeonian) (Table 2). Thus, the variation among formulations (on the order of 0.01 mm/year or less) is comparable to variations attributable to methodologic differences between the studies. We identified only

Weighted Average of 2-D Linear Penetration Rates of HXLPE Liners in Hips

Fig. 2 This forest plot illustrates the variation in reported penetration rates of HXLPE in different studies used to calculate the weighted average of 0.042 mm/year.

Fig. 3 This forest plot illustrates the variation in reported penetration rates of conventional UHMWPE in different studies used to calculate the weighted average of 0.137 mm/year.

Fig. 4 This forest plot illustrates the variation in the standardized difference in mean of the 2D linear penetration rates of crosslinked and conventional polyethylene liners. Across every study, the difference in means consistently favors crosslinked over conventional polyethylene.

one study in which two HXLPE formulations were directly compared using the same followup period and radiographic methodology. Whittaker et al. [137] compared radiographic outcomes in two cohorts of patients receiving total hip systems manufactured by Smith & Nephew Inc (Memphis, TN) ($n = 47$ cases including an XLPE liner) or Zimmer Inc ($n = 36$ cases including Longevity® liners) and with minimum 5-year followup. The authors did not observe a difference in steady-state 2D penetration rates between the XLPE or Longevity® cohorts.

The weighted averages of the penetration rates for small and large cobalt-chromium femoral heads into HXLPE liners were 0.048 mm/year (95% CI, 0.038–0.058) and 0.027 mm/year (95% CI, –0.010–0.064), respectively (Table 3). Bragdon et al. [19] compared linear penetration

rates of different heads sizes with Durasul® liners (Zimmer Inc) after a 3.7-year followup and found the penetration rates were 0.03 mm/year in 28-mm heads and 0.01 mm/year in 32-mm heads. Hammerberg et al. [58] reported a linear penetration rate after an average 3.6-year followup of 0.023 and 0.021 mm/year for 28- to 32-mm and 38- to 44-mm femoral heads on Durasul® liners. With a longer mean followup time of 5.7 years, Lachiewicz et al. [83] reported linear penetration rates of 0.06, 0.032, 0.011, and 0.075 mm/year for 26-, 28-, 32-, and 36- to 40-mm heads, respectively, on Longevity® liners. An RCT by Bragdon et al. [21] reported linear penetration rates of 0.020 and 0.005 mm/year for 28- and 38-mm heads, respectively, with Durasul® and Longevity® liners after a followup of 6.9 years.

Table 2. Summary of weighted-average 2D linear penetration rates of HXLPE cups in hips: influence of HXLPE formulation

HXLPE formulation	Weighted-average 2D linear penetration rate (mm/year)*	Study	Femoral head type	Study type			
Aeonian	0.063 (0.009)	Ise et al. [66] (2009)	Zirconia Type 1	RCT			
				RCT			
				RCT			
				RCT			
				RCT			
		Ise et al. [66] (2009)	Zirconia Type 2	RCT			
		Ise et al. [66] (2009)	Stainless steel	RCT			
		Kawate et al. [69] (2009)	Zirconia	RCT			
		Kawate et al. [69] (2009)	Cobalt-chromium	RCT			
		Oonishi et al. [110] (2006)		COH			
Crossfire	0.057 (0.014)	D’Antonio et al. [37] (2005)		COH			
			Krushell et al. [73] (2005)		COH		
			Martell et al. [91] (2003)		RCT		
			Rajadhyaksha et al. [114] (2009)		COH		
			Rohrl et al. [122] (2007)		COH		
			Durasul	0.023 (0.001)	Bragdon et al. [19] (2006)	28-mm	COH
						32-mm	COH
Dorr et al. [41] (2005)		COH					
Hammerberg et al. [58] (2010)	28- to 32-mm	COH					
Hammerberg et al. [58] (2010)	38- to 44-mm	COH					
Triclot et al. [132] (2007)		RCT					
Longevity	0.042 (0.005)	Beksac et al. [10] (2009)				COH	
			Garvin et al. [48] (2009)		COH		
			Glyn-Jones et al. [52] (2008)		RCT		
		Lachiewicz et al. [83] (2009)	26-mm	COH			
		Lachiewicz et al. [83] (2009)	28-mm	COH			
		Lachiewicz et al. [83] (2009)	32-mm	COH			
		Lachiewicz et al. [83] (2009)	36- to 40-mm	COH			
		Mall et al. [89] (2011)		COH			
		Nakahara et al. [106] (2010)	Cobalt-chromium	RCT			
		Nakahara et al. [106] (2010)	Zirconia	RCT			
		Olyslaegers et al. [108] (2008)		COH			
		Shia et al. [127] (2009)		COH			
		Marathon	0.038 (0.012)	Bitsch et al. [13] (2008)		COH	
				Engh et al. [44] (2006)		RCT	
				Heisel et al. [61] (2005)		COH	
				Hopper et al. [64] (2003)		COH	
				Kim et al. [71] (2009)		RCT	
Leung et al. [85] (2007)				COH			

* Values are expressed as mean, with standard error in parentheses; 2D = two-dimensional; HXLPE = highly crosslinked polyethylene; RCT = randomized controlled trial; COH = prospective or retrospective cohort study.

The overall weighted average of the linear penetration rate for metal (primarily cobalt-chromium) femoral heads on HXLPE was calculated as 0.038 mm/year (95% CI, 0.032–0.045) from eight RCTs and 16 cohort studies. An RCT by Ise et al. [66] reported a linear penetration rate of 0.068 (standard error, 0.009) for stainless steel on HXLPE.

The overall weighted-average penetration rate of six studies with ceramic femoral heads on HXLPE liners was 0.058 mm/year (95% CI, 0.040–0.076) (Table 4). An RCT study by Kim et al. [71] reported a 2D linear penetration rate for alumina on HXLPE as 0.06 mm/year (standard error, 0.003). Similarly, Oonishi et al. [110] reported a penetration

Table 3. Summary of weighted-average 2D linear penetration rates of HXLPE cups in hips: influence of femoral head size

Femoral head size	Weighted-average 2D linear penetration rate (mm/year)*	Study	Femoral head type	Study type
Small (22–28 mm)	0.048 (0.005)	Bragdon et al. [19] (2006)	28-mm	COH
		Bragdon et al. [21] (2007)	28-mm	RCT
		D'Antonio et al. [37] (2005)		COH
		Dorr et al. [41] (2005)		COH
		Engh et al. [44] (2006)		RCT
		Glyn-Jones et al. [52] (2008)		RCT
		Hopper et al. [64] (2003)		COH
		Ise et al. [66] (2009)	Zirconia Type 1	RCT
		Ise et al. [66] (2009)	Zirconia Type 2	RCT
		Ise et al. [66] (2009)	Stainless steel	RCT
		Kawate et al. [69] (2009)	Zirconia	RCT
		Kawate et al. [69] (2009)	Cobalt-chromium	RCT
		Kim et al. [71] (2009)		RCT
		Krushell et al. [73] (2005)		COH
		Lachiewicz et al. [83] (2009)	26-mm	COH
		Lachiewicz et al. [83] (2009)	28-mm	COH
		Leung et al. [85] (2007)		COH
		Mall et al. [89] (2011)		COH
		Manning et al. [90] (2005)		COH
		Martell et al. [91] (2003)		RCT
		Olyslaegers et al. [108] (2008)		COH
		Oonishi et al. [110] (2006)		COH
		Rajadhyaksha et al. [114] (2009)		COH
		Rohrl et al. [122] (2007)		COH
		Shia et al. [127] (2009)		COH
		Triclot et al. [132] (2007)		RCT
Large (32–40 mm)	0.027 (0.019)	Bragdon et al. [19] (2006)	32-mm	COH
		Bragdon et al. [21] (2007)	38-mm	RCT
		Lachiewicz et al. [83] (2009)	32-mm	COH
		Lachiewicz et al. [83] (2009)	36- to 40-mm	COH

* Values are expressed as mean, with standard error in parentheses; 2D = two-dimensional; HXLPE = highly crosslinked polyethylene; RCT = randomized controlled trial; COH = prospective or retrospective cohort study.

rate of 0.10 (standard error, 0.006) for alumina on HXLPE. Nakahara et al. [106] compared steady-state penetration rates for Longevity® paired with a zirconia femoral head. Two RCTs have reported penetration rate data for zirconia femoral heads articulating with Aeonian (Japan Medical Materials Corp, Osaka, Japan) [66] (Table 4).

Weighted-averages Analysis of Studies Reporting Osteolysis Outcomes for HXLPEs in Hip Arthroplasty

The incidence of osteolysis in patients with UHMWPE liners and HXLPE liners was analyzed by calculating odds ratios from individual cohort ($n = 8$) and RCT ($n = 1$) studies with 5-year minimum followup (Fig. 5). The studies

were combined and the pooled odds ratio was estimated to be 0.131 (95% CI, 0.064–0.268) using a random-effects model, indicating the incidence of osteolysis is 87% lower in patients with HXLPE liners when compared with patients with conventional polyethylene liners. Subgroup analysis was also conducted for patient demographics, study design, and device design factors (Table 5). The variation in the odds ratio for osteolysis was not attributable to any of the factors we considered.

Summary of Radiographic Outcome Studies for HXLPEs in Knee Arthroplasty

Only two knee studies were identified in the literature search of HXLPEs in total joint arthroplasty [62, 99],

Table 4. Summary of weighted-average 2D linear penetration rates of HXLPE cups in hips: influence of femoral head material

Ceramic head material (manufacturer)	Weighted-average 2D linear penetration rate (mm/year)*	HXLPE liner	Study	Study type
Oxidized zirconium (Oxinium TM ; Smith and Nephew, Inc, Memphis, TN)	0.041 (0.026)	Longevity	Garvin et al. [48] (2009)	Cohort
Zirconia (PHS head; Japan Medical Materials Corp, Osaka, Japan)	0.067 (0.009)	Aeonian	Ise et al. [66] (2009)	RCT
Zirconia (HHZ head; Kobelco, Kobe Steel Ltd, Tokyo, Japan)	0.059 (0.006)	Aeonian	Ise et al. [66] (2009)	RCT
Zirconia (3Y-TZP; Japan Medical Materials Corp, Osaka, Japan)	0.042 (0.004)	Aeonian	Kawate et al. [69] (2009)	RCT
Zirconia (NGK Spark Plug, Wixom, MI)	0.030 (0.002)	Longevity	Nakahara et al. [106] (2010)	RCT
Alumina (Kyocera Corp, Kyoto, Japan)	0.10 (0.006)	Aeonian	Oonishi et al. [110] (2006)	COH
Overall ceramic	0.058 (0.009)		6 total studies	2 COH, 4 RCT

* Values are expressed as mean, with standard error in parentheses; 2D = two-dimensional; HXLPE = highly crosslinked polyethylene; RCT = randomized controlled trial; COH = prospective or retrospective cohort study.

Fig. 5 The odds ratio for osteolysis (conventional versus HXLPE) was 0.131 across nine studies. Note an odds ratio of less than 1 implies a lower risk of osteolysis for HXLPE relative to conventional UHMWPE. PE = polyethylene.

insufficient for a systematic review and analysis. These studies are nevertheless summarized briefly for completeness and to document the current state of the art in the literature for HXLPEs used in knee arthroplasty.

Hodrick et al. [62] retrospectively studied the clinical and radiographic outcomes for Durasul[®] and gamma-inert-sterilized UHMWPE in the Natural-Knee[®] (Zimmer Inc), which is a cruciate-retaining design. One hundred consecutive patients were selected for each cohort based on the date of availability of the HXLPE at their institution in February 2001. Between 30% and 34% of the patients in both groups received cement fixation. The mean followup was 7.6 years for the conventional cohort and 6.3 years for

Table 5. Subgroup analysis of odds ratios for osteolysis

Moderator	Categories	Odds ratio (95% CI)*
Mean patient age	≤ 60 years	0.123 (0.037–0.405)
	> 60 years	0.088 (0.028–0.277)
Mean patient body mass index	≤ 25 kg/m ²	0.081 (0.004–1.777) [†]
	> 25 kg/m ²	0.096 (0.027–0.340)
2D linear penetration rate determination method	Martell	0.088 (0.025–0.311)
	Other	0.152 (0.056–0.409)
Femoral head material	Ceramic	0.081 (0.004–1.777) [†]
	Metal	0.193 (0.120–0.313)

* Differences in these odds ratios were not significant ($p > 0.05$);

[†]based on results from one clinical trial that met the inclusion criteria; CI = confidence interval.

the HXLPE cohort. There were nine revisions in the conventional cohort and five in the HXLPE cohort. The revision rates of the two cohorts were similar.

Minoda et al. [99] compared the clinical and radiographic outcomes for Prolong[®] (Zimmer Inc) and gamma-inert-sterilized UHMWPE in the NexGen[®] cruciate-retaining knee design (Zimmer Inc). The single-institution study design included two consecutive series ($n = 89$ HXLPE, $n = 113$ conventional polyethylene) performed by the same surgical team with the same operative technique. Among implant factors, only the tibial insert material differed between cohorts. At 2-year followup, no differences were observed in ROM, knee alignment, and Knee Society score. There were no revisions and no radiographic observations of osteolysis.

Discussion

The primary intent of this review was to provide a concise overview of the major themes in polyethylene biomaterials, including the development of HXLPE. For three decades after its introduction by Charnley for metal-on-plastic low-friction arthroplasty, advances in polyethylene technology were relatively modest. The development of HXLPEs in the late 1990s ushered in a period of scientific growth and renewed interest in further optimizing and standardizing the polymer for hip and knee arthroplasty. The second and third aims of this study were to systematically review hip arthroplasty studies reporting radiographic wear and osteolysis outcomes of HXLPEs. Available evidence in 44 primary research studies uniformly supports elevated radiation crosslinking technology as an effective method to reduce femoral head penetration and osteolysis in THA; however, the improvement in long-term survivorship remains to be demonstrated. Based on currently available literature, reduction in femoral head penetration or osteolysis risk is not supported for large-diameter (> 32 mm) metallic femoral heads or ceramic femoral heads of any size based on currently available literature. The fourth aim was to systematically review the radiographic outcomes of HXLPEs used in the knee. Because only two studies reporting clinical outcomes of HXLPEs in knee arthroplasty could be identified, it remains too early to perform a meta-analysis of the knee literature.

This review and the literature are limited. First, it was not feasible to exhaustively cite all the relevant scientific and preclinical testing references for each type of commercially available polyethylene formulation. The interested reader should appreciate a detailed treatment of polyethylene technology over a five-decade period can fill an entire textbook [76]. Second, the historical focus in the first part of the review precluded a formal, Cochrane-style search strategy. Third, the review of radiographic wear rates and incidence of osteolysis in hip and knee arthroplasty was limited to polyethylene formulations used by major manufacturers and documented in journal publications. Fourth, we accepted both prospective randomized studies and cohort studies for our weighted-averages analysis of wear and osteolysis. Fifth, this review is based on first-generation HXLPEs, and more recent second-generation HXLPEs were excluded. Sixth, as highlighted by our own analysis, methodologic variations among different studies are at least as great as the differences between HXLPE formulation, femoral head size, and femoral head material. Seventh, the reported outcomes of radiographic wear analysis are heterogeneous across studies (ie, 2D versus three-dimensional penetration rates, overall versus steady-state penetration rates), greatly complicating interstudy comparisons of findings such as

the present review. Thus, for all of these reasons, our results are not intended to be interpreted as a formal meta-analysis but a quantitative systematic review.

Although encouraging, the story is by no means over for first-generation HXLPEs. One decade after their clinical introduction, our knowledge of the clinical failure modes and reasons of revision for first-generation HXLPEs remains extremely limited. For annealed polyethylene, which contains residual free radicals, *in vivo* oxidation has been observed at the rim [78], and rim delamination has been identified in case studies of chronic instability and impingement [35]. The mechanical properties and oxidation of the bearing surface in retrieved annealed bearings have not yet shown evidence of degradation with implantation [78], suggesting the femoral head reduces *in vivo* oxidation at this location. For remelted polyethylenes, rim fracture has been reported in several case studies requiring revision of the bearing [42, 57, 58, 101, 131]. Common threads among rim fracture case studies include thin remelted liners, sometimes with an elevated rim, and vertical orientation (malpositioning) of the shell. Evidence of rim fatigue and fracture has been observed in remelted polyethylene; however, the prevalence of this failure mode remains poorly understood. Although not generally associated with revision, the findings of rim oxidation (in annealed liners) and cracks (in remelted liners) provide motivation to continue to monitor first-generation highly crosslinked materials into their second decade of service, because the long-term clinical importance of these observations remains unclear. Furthermore, evidence of low but measurable oxidation at the bearing surface of retrieved remelted liners has as yet unknown implications for the second decade of service [88]. These unanswered questions provide motivation for ongoing research on the long-term stability and mechanical performance of first-generation polyethylene materials.

From a clinical perspective, many unanswered questions for first-generation polyethylene biomaterials relate to component design, specifically as they relate to thin hip liners with large-diameter femoral heads, the effectiveness of ceramic femoral heads, and inserts for knee arthroplasty. Based on the documented success of HXLPEs with 28-mm femoral heads (Table 3), over the past decade, there has been a shift to use larger head sizes with an effort to reduce the incidence of dislocation. Nevertheless, to date, less than a handful of clinical studies have reported data for HXLPE studies based on 32-mm or greater femoral head sizes [19] (Table 3). In 2004, a survey of orthopaedic manufacturers found the largest head diameters offered in the United States ranged from 36 to 44 mm and the thinnest hip bearings ranged from 5 to 6 mm [74]. When the study was repeated in 2009, the largest head diameters ranged from 36 to 48 mm and the thinnest hip bearings ranged from 3.8

to 6 mm [76]. Thus, concerns about the minimum thickness of polyethylene are currently perceived to limit the introduction of acetabular liners with femoral head sizes greater than 48 mm.

This systematic review identified numerous studies documenting the clinical performance of HXLPEs for hip arthroplasty, but only two clinical outcomes studies were identified for HXLPE use in the knee [62, 99]. The authors of both knee studies emphasized their research demonstrated the short-term safety of HXLPE in the knee. However, because neither study quantified femoral component penetration or detected osteolysis, it is not yet possible to judge the clinical efficacy and value of HXLPE in knee arthroplasty. Initially, only two manufacturers (Sulzer, Winterthur, Switzerland; and Zimmer Inc) were distributing highly crosslinked tibial inserts in the United States due to concerns about the reduced fatigue and fracture behavior, especially with remelted polyethylenes. Over the past 5 years, acceptance of crosslinking technology for knees has increased substantially, but still only three of five major orthopaedic manufacturers currently offer first-generation highly crosslinked tibial inserts [76]. In light of the crucial and ever-expanding role that polyethylene biomaterials play in knee arthroplasty and the perception among certain health economists that the use of HXLPE for TKA is an expensive “premium” technology of questionable value [50], the currently limited clinical evidence supporting the use of HXLPEs for the knee is remarkable.

The next evolutionary phase of polyethylene biomaterials development, which is ongoing, has focused on techniques to stabilize highly crosslinked polyethylene without sacrificing material properties by remelting [43, 80, 112]. Given the 10-year followup that has been necessary to assure members of the orthopaedic community of the long-term effectiveness of first-generation HXLPEs, it may seem premature for polyethylene scientists to have already moved on to propose new generations of polymer technology for hip and knee bearings. It remains to be determined what clinical benefits, if any, will be provided by second-generation polyethylene technologies beyond those already afforded by first-generation HXLPE.

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References

1. Ainsworth R, Farling G, Bardos D. An improved bearing material for joint replacement prostheses: carbon fiber-reinforced UHMW polyethylene. In: *Transactions of the 3rd Annual Meeting of the Society for Biomaterials*. Minneapolis, MN: Society for Biomaterials; 1977:119.
2. American Society for Testing and Materials. ASTM F2565-06. *Standard Guide for Extensively Irradiation-Crosslinked Ultra-High Molecular Weight Polyethylene Fabricated Forms for Surgical Implant Applications*. West Conshohocken, PA: American Society for Testing and Materials; 2006.
3. Amstutz HC, Campbell P, McKellop H, Schmalzreid TP, Gillespie WJ, Howie D, Jacobs J, Medley J, Merritt K. Metal on metal total hip replacement workshop consensus document. *Clin Orthop Relat Res*. 1996;329(Suppl):S297–S303.
4. August AC, Aldam CH, Pynsent PB. The McKee-Farrar hip arthroplasty: a long-term study. *J Bone Joint Surg Br*. 1986;68: 520–527.
5. Ayers DC, Hays PL, Drew JM, Eskander MS, Osuch D, Bragdon CR. Two-year radiostereometric analysis evaluation of femoral head penetration in a challenging population of young total hip arthroplasty patients. *J Arthroplasty*. 2009;24:9–14.
6. Baker DA, Bellare A, Pruitt L. The effects of degree of cross-linking on the fatigue crack initiation and propagation resistance of orthopedic-grade polyethylene. *J Biomed Mater Res A*. 2003; 66:146–154.
7. Baker DA, Hastings RS, Pruitt L. Study of fatigue resistance of chemical and radiation crosslinked medical grade ultrahigh molecular weight polyethylene. *J Biomed Mater Res*. 1999;46: 573–581.
8. Bartel DL, Bicknell VL, Wright TM. The effect of conformity, thickness, and material on stresses in ultra-high molecular weight components for total joint replacement. *J Bone Joint Surg Am*. 1986;68:1041–1051.
9. Bartel DL, Rawlinson JJ, Burstein AH, Ranawat CS, Flynn WF Jr. Stresses in polyethylene components of contemporary total knee replacements. *Clin Orthop Relat Res*. 1995;317:76–82.
10. Beksac B, Salas A, Gonzalez Della Valle A, Salvati EA. Wear is reduced in THA performed with highly cross-linked polyethylene. *Clin Orthop Relat Res*. 2009;467:1765–1772.
11. Bell CJ, Walker PS, Abeysondera MR, Simmons JM, King PM, Blunn GW. Effect of oxidation on delamination of ultrahigh-molecular-weight polyethylene tibial components. *J Arthroplasty*. 1998;13:280–290.
12. Bhamri SK, Gsell R, Kirkpatrick L, Swarts D, Blanchard CR, Crowninshield RD. The effect of aging on mechanical properties of melt-annealed highly crosslinked UHMWPE. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Crosslinked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements*. West Conshohocken, PA: American Society for Testing and Materials; 2004.
13. Bitsch RG, Loidolt T, Heisel C, Ball S, Schmalzried TP. Reduction of osteolysis with use of Marathon cross-linked polyethylene: a concise follow-up, at a minimum of five years, of a previous report. *J Bone Joint Surg Am*. 2008;90:1487–1491.
14. Bizot P, Nizard R, Lerouge S, Prudhommeaux F, Sedel L. Ceramic/ceramic total hip arthroplasty. *J Orthop Sci*. 2000;5: 622–627.
15. Blunn GW, Joshi AB, Minns RJ, Lidgren L, Lilley P, Ryd L, Engelbrecht E, Walker PS. Wear in retrieved condylar knee arthroplasties: a comparison of wear in different designs of 280 retrieved condylar knee prostheses. *J Arthroplasty*. 1997;12: 281–290.
16. Bostrom MP, Bennett AP, Rimnac CM, Wright TM. The natural history of ultra high molecular weight polyethylene. *Clin Orthop Relat Res*. 1994;309:20–28.
17. Boutin P, Christel P, Dorlot JM, Meunier A, de Roquancourt A, Blanquaert D, Herman S, Sedel L, Witvoet J. The use of dense alumina-alumina ceramic combination in total hip replacement. *J Biomed Mater Res*. 1988;22:1203–1232.
18. Bozic KJ, Kurtz S, Lau E, Ong K, Chiu V, Vail TP, Rubash HE, Berry DJ. The epidemiology of bearing surface usage in total hip

- arthroplasty in the United States. *J Bone Joint Surg Am.* 2009; 91:1614–1620.
19. Bragdon CR, Barrett S, Martell JM, Greene ME, Malchau H, Harris WH. Steady-state penetration rates of electron beam-irradiated, highly cross-linked polyethylene at an average 45-month follow-up. *J Arthroplasty.* 2006;21:935–943.
 20. Bragdon CR, Greene ME, Freiberg AA, Harris WH, Malchau H. Radiostereometric analysis comparison of wear of highly cross-linked polyethylene against 36- vs 28-mm femoral heads. *J Arthroplasty.* 2007;22:125–129.
 21. Bragdon CR, Kwon YM, Geller JA, Greene ME, Freiberg AA, Harris WH, Malchau H. Minimum 6-year followup of highly cross-linked polyethylene in THA. *Clin Orthop Relat Res.* 2007;465:122–127.
 22. Calvert GT, Devane PA, Fielden J, Adams K, Horne JG. A double-blind, prospective, randomized controlled trial comparing highly cross-linked and conventional polyethylene in primary total hip arthroplasty. *J Arthroplasty.* 2009;24:505–510.
 23. Champion AR, Li S, Saum K, Howard E, Simmons W. The effect of crystallinity on the physical properties of UHMWPE. *Trans Orthop Res Soc.* 1994;19:585.
 24. Chan FW, Bobyn JD, Medley JB, Krygier JJ, Yue S, Tanzer M. Engineering issues and wear performance of metal on metal hip implants. *Clin Orthop Relat Res.* 1996;333:96–107.
 25. Charnley J. Arthroplasty of the hip: a new operation. *Lancet* 1961;I:1129–1132.
 26. Charnley J. Tissue reaction to the polytetrafluoroethylene. *Lancet.* 1963;II:1379.
 27. Charnley J. Low friction principle. In: *Low Friction Arthroplasty of the Hip: Theory and Practice.* Berlin, Germany: Springer-Verlag; 1979:3–16.
 28. Charnley J. Personal communication, 1971: Sterilization of Charnley total hip sockets of high density polyethylene. In: Kurtz SM, ed. *The UHMWPE Biomaterials Handbook: Ultra-High Molecular Weight Polyethylene in Total Joint Replacement and Medical Devices.* 2nd ed. Burlington, MA: Academic Press; 2009:39–40.
 29. Charnley J, Halley DK. Rate of wear in total hip replacement. *Clin Orthop Relat Res.* 1975;112:170–179.
 30. Collier JP, Sperling DK, Currier JH, Sutula LC, Saum KA, Mayor MB. Impact of gamma sterilization on clinical performance of polyethylene in the knee. *J Arthroplasty.* 1996;11:377–389.
 31. Collier JP, Sutula LC, Currier BH, Currier JH, Wooding RE, Williams IR, Farber KB, Mayor MB. Overview of polyethylene as a bearing material: comparison of sterilization methods. *Clin Orthop Relat Res.* 1996;333:76–86.
 32. Collier MB, Engh CA Jr, Engh GA. Shelf age of the polyethylene tibial component and outcome of unicondylar knee arthroplasty. *J Bone Joint Surg Am.* 2004;86:763–769.
 33. Connelly GM, Rinnac CM, Wright TM, Hertzberg RW, Manson JA. Fatigue crack propagation behavior of ultrahigh molecular weight polyethylene. *J Orthop Res.* 1984;2:119–125.
 34. Costa L, Brach de Prever EM. *UHMWPE for Arthroplasty.* Turin, Italy: Edizioni Minerva Medica; 2000.
 35. Currier BH, Currier JH, Mayor MB, Lyford KA, Collier JP, Van Citters DW. Evaluation of oxidation and fatigue damage of retrieved crossfire polyethylene acetabular cups. *J Bone Joint Surg Am.* 2007;89:2023–2029.
 36. Currier BH, Currier JH, Mayor MB, Lyford KA, Van Citters DW, Collier JP. In vivo oxidation of gamma-barrier-sterilized ultra-high-molecular-weight polyethylene bearings. *J Arthroplasty.* 2007;22:721–731.
 37. D'Antonio JA, Manley MT, Capello WN, Bierbaum BE, Ramakrishnan R, Naughton M, Sutton K. Five-year experience with Crossfire highly cross-linked polyethylene. *Clin Orthop Relat Res.* 2005;441:143–150.
 38. Digas G, Karrholm J, Thanner J, Herberts P. 5-year experience of highly cross-linked polyethylene in cemented and uncemented sockets: two randomized studies using radiostereometric analysis. *Acta Orthop.* 2007;78:746–754.
 39. Digas G, Karrholm J, Thanner J, Malchau H, Herberts P. Highly cross-linked polyethylene in total hip arthroplasty: randomized evaluation of penetration rate in cemented and uncemented sockets using radiostereometric analysis. *Clin Orthop Relat Res.* 2004;429:6–16.
 40. Dorr LD, Hilton KR, Wan Z, Markovich GD, Bloebaum R. Modern metal on metal articulation for total hip replacements. *Clin Orthop Relat Res.* 1996;333:108–117.
 41. Dorr LD, Wan Z, Shahrar 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.
 42. Duffy GP, Wannomae KK, Rowell SL, Muratoglu OK. Fracture of a cross-linked polyethylene liner due to impingement. *J Arthroplasty.* 2009;24:158.e15–19.
 43. Dumbleton JH, D'Antonio JA, Manley MT, Capello WN, Wang A. The basis for a second-generation highly cross-linked UHMWPE. *Clin Orthop Relat Res.* 2006;453:265–271.
 44. Engh CA Jr, Stepniewski AS, Ginn SD, Beykirch SE, Sychterz-Terefenko CJ, Hopper RH Jr, Engh CA. A randomized prospective evaluation of outcomes after total hip arthroplasty using cross-linked marathon and non-cross-linked Enduron polyethylene liners. *J Arthroplasty.* 2006;21:17–25.
 45. Fukui K, Kaneuji A, Sugimori T, Ichiseki T, Kitamura K, Matsumoto T. Wear comparison between a highly cross-linked polyethylene and conventional polyethylene against a zirconia femoral head: minimum 5-year follow-up. *J Arthroplasty.* 2011; 26:45–49.
 46. Garcia-Rey E, Garcia-Cimbrelo E, Cruz-Pardos A, Ortega-Chamarro J. New polyethylenes in total hip replacement: a prospective, comparative clinical study of two types of liner. *J Bone Joint Surg Br.* 2008;90:149–153.
 47. Garino JP. Modern ceramic-on-ceramic total hip systems in the United States: early results. *Clin Orthop Relat Res.* 2000;379: 41–47.
 48. Garvin KL, Hartman CW, Mangla J, Murdoch N, Martell JM. Wear analysis in THA utilizing oxidized zirconium and cross-linked polyethylene. *Clin Orthop Relat Res.* 2009;467:141–145.
 49. Geller JA, Malchau H, Bragdon C, Greene M, Harris WH, Freiberg AA. Large diameter femoral heads on highly cross-linked polyethylene: minimum 3-year results. *Clin Orthop Relat Res.* 2006;447:53–59.
 50. Gioe TJ, Sharma A, Tatman P, Mehle S. Do “premium” joint implants add value? Analysis of high cost joint implants in a community registry. *Clin Orthop Relat Res.* 2011;469:48–54.
 51. Glyn-Jones S, Isaac S, Hauptfleisch J, McLardy-Smith P, Murray DW, Gill HS. Does highly cross-linked polyethylene wear less than conventional polyethylene in total hip arthroplasty? A double-blind, randomized, and controlled trial using roentgen stereophotogrammetric analysis. *J Arthroplasty.* 2008;23:337–343.
 52. Glyn-Jones S, McLardy-Smith P, Gill HS, Murray DW. The creep and wear of highly cross-linked polyethylene: a three-year randomised, controlled trial using radiostereometric analysis. *J Bone Joint Surg Br.* 2008;90:556–561.
 53. Good V, Widding K, Scott M, Jani S. The sensitivity of cross-linked UHMWPE to abrasive wear: hips vs. knees. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Cross-linked and Thermally Treated Ultra-High Molecular Weight*

- Polyethylene For Joint Replacements*. West Conshohocken, PA: American Society for Testing and Materials; 2004.
54. Greer K, King R, Chan FW. Effects of raw material, irradiation dose, and irradiation source on crosslinking of UHMWPE. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Crosslinked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements*. West Conshohocken, PA: American Society for Testing and Materials; 2004.
 55. Griffith MJ, Seidenstein MK, Williams D, Charnley J. Socket wear in Charnley low friction arthroplasty of the hip. *Clin Orthop Relat Res*. 1978;137:37–47.
 56. Grobbelaar CJ, Du Plessis TA, Marais F. The radiation improvement of polyethylene prostheses: a preliminary study. *J Bone Joint Surg Br*. 1978;60:370–374.
 57. Halley D, Glassman A, Crowninshield RD. Recurrent dislocation after revision total hip replacement with a large prosthetic femoral head: a case report. *J Bone Joint Surg Am*. 2004;86:827–830.
 58. Hammerberg EM, Zhinian W, Manish D, Lawrence DD. Wear and range of motion of different femoral head sizes. *J Arthroplasty*. 2010;25:839–843.
 59. Harris WH. The problem is osteolysis. *Clin Orthop Relat Res*. 1995;311:46–53.
 60. Heisel C, Silva M, dela Rosa MA, Schmalzried TP. Short-term in vivo wear of cross-linked polyethylene. *J Bone Joint Surg Am*. 2004;86:748–751.
 61. Heisel C, Silva M, Schmalzried TP. In vivo wear of bilateral total hip replacements: conventional versus crosslinked polyethylene. *Arch Orthop Trauma Surg*. 2005;125:555–557.
 62. Hodrick JT, Severson EP, McAlister DS, Dahl B, Hofmann AA. Highly crosslinked polyethylene is safe for use in total knee arthroplasty. *Clin Orthop Relat Res*. 2008;466:2806–2812.
 63. Hopper RH Jr, Young AM, Orishimo KF, Engh CA Jr. Effect of terminal sterilization with gas plasma or gamma radiation on wear of polyethylene liners. *J Bone Joint Surg Am*. 2003;85:464–468.
 64. Hopper RH Jr, Young AM, Orishimo KF, McAuley JP. Correlation between early and late wear rates in total hip arthroplasty with application to the performance of marathon cross-linked polyethylene liners. *J Arthroplasty*. 2003;18:60–67.
 65. Ianuzzi A, Kurtz SM. Sterilization of joint replacement materials. In: Revell PA, ed. *Joint Replacement Technology*. Cambridge, UK: Woodhead Publishing Ltd; 2008:407–430.
 66. Ise K, Kawanabe K, Tamura J, Akiyama H, Goto K, Nakamura T. Clinical results of the wear performance of cross-linked polyethylene in total hip arthroplasty: prospective randomized trial. *J Arthroplasty*. 2009;24:1216–1220.
 67. Jacobs JJ, Shanbhag A, Glant TT, Black J, Galante JO. Wear debris in total joint replacements. *J Am Acad Orthop Surg*. 1994;2:212–220.
 68. Jani S, Scott M. Wear debris generation in joint simulator testing of crosslinked UHMWPE. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Crosslinked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements*. West Conshohocken, PA: American Society for Testing and Materials; 2004.
 69. Kawate K, Ohmura T, Kawahara I, Tamai K, Ueha T, Takemura K. Differences in highly cross-linked polyethylene wear between zirconia and cobalt-chromium femoral heads in Japanese patients: a prospective, randomized study. *J Arthroplasty*. 2009;24:1221–1224.
 70. Kiely PD, Harty JA, McElwain JP. Hylamer wear rates and shelf life: a clinical correlation. *Acta Orthop Belg*. 2005;71:429–434.
 71. Kim YH, Kim JS, Choi YW, Kwon OR. Intermediate results of simultaneous alumina-on-alumina bearing and alumina-on-highly cross-linked polyethylene bearing total hip arthroplasties. *J Arthroplasty*. 2009;24:885–891.
 72. Kothari M, Bartel DL, Booker JF. Surface geometry of retrieved McKee-Farrar total hip replacements. *Clin Orthop Relat Res*. 1996;329(Suppl):S141–S147.
 73. Krushell RJ, Fingerth RH, Cushing MC. Early femoral head penetration of a highly crosslinked polyethylene liner vs a conventional polyethylene liner. *J Arthroplasty*. 2005;20:73–76.
 74. Kurtz SM. *The UHMWPE Handbook: Ultra-High Molecular Weight Polyethylene in Total Joint Replacement*. New York, NY: Academic Press; 2004.
 75. Kurtz SM. Packaging and sterilization of UHMWPE. In: Kurtz SM, ed. *The UHMWPE Biomaterials Handbook: Ultra-High Molecular Weight Polyethylene in Total Joint Replacement and Medical Devices*. 2nd ed. Burlington, MA: Academic Press; 2009:21–30.
 76. Kurtz SM, ed. *The UHMWPE Biomaterials Handbook: Ultra-High Molecular Weight Polyethylene in Total Joint Replacement and Medical Devices*. 2nd ed. Burlington, MA: Academic Press; 2009.
 77. Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Crosslinked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements*. West Conshohocken, PA: American Society for Testing and Materials; 2004.
 78. Kurtz SM, Hozack WJ, Purtill JJ, Marcolongo M, Kraay MJ, Goldberg VM, Sharkey PF, Parvizi J, Rimnac CM, Edidin AA. Significance of in vivo degradation for polyethylene in total hip arthroplasty. *Clin Orthop Relat Res*. 2006;453:47–57.
 79. Kurtz SM, Manley M, Wang A, Taylor S, Dumbleton J. Comparison of the properties of annealed crosslinked (Crossfire) and conventional polyethylene as hip bearing materials. *Bull Hosp Jt Dis*. 2002–2003;61:17–26.
 80. Kurtz SM, Mazzucco D, Rimnac CM, Schroeder D. Anisotropy and oxidative resistance of highly crosslinked UHMWPE after deformation processing by solid-state ram extrusion. *Biomaterials*. 2006;27:24–34.
 81. Kurtz SM, Muratoglu OK, Evans M, Edidin AA. Advances in the processing, sterilization, and crosslinking of ultra-high molecular weight polyethylene for total joint arthroplasty. *Biomaterials*. 1999;20:1659–1688.
 82. 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.
 83. Lachiewicz PF, Heckman DS, Soileau ES, Mangla J, Martell JM. Femoral head size and wear of highly cross-linked polyethylene at 5 to 8 years. *Clin Orthop Relat Res*. 2009;467:3290–3296.
 84. Laurent MP, Blanchard CR, Yao JQ, Johnson TS, Gilbertson LN, Swarts D, Crowninshield RD. The wear of highly cross-linked UHMWPE in the presence of abrasive particles: hip and knee simulator studies. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Crosslinked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements*. West Conshohocken, PA: American Society for Testing and Materials; 2004.
 85. Leung SB, Egawa H, Stepniewski A, Beykirch S, Engh CA Jr, Engh CA Sr. Incidence and volume of pelvic osteolysis at early follow-up with highly cross-linked and noncross-linked polyethylene. *J Arthroplasty*. 2007;22:134–139.
 86. Li S, Burstein AH. Ultra-high molecular weight polyethylene: the material and its use in total joint implants. *J Bone Joint Surg Am*. 1994;76:1080–1090.
 87. Li S, Chang JD, Barrena EG, Furman BD, Wright TM, Salvati E. Nonconsolidated polyethylene particles and oxidation in

- Charnley acetabular cups. *Clin Orthop Relat Res.* 1995;319:54–63.
88. MacDonald D, Kurtz SM, Sakona A, Rimnac C. In vivo oxidation, oxidation potential, and mechanical properties of first generation highly crosslinked polyethylenes. *Clin Orthop Relat Res.* 2010 December 16 [Epub ahead of print].
 89. Mall NA, Nunley RM, Zhu JJ, Maloney WJ, Barrack RL, Clohisy JC. The incidence of acetabular osteolysis in young patients with conventional versus highly crosslinked polyethylene. *Clin Orthop Relat Res.* 2011;469:372–381.
 90. 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.
 91. Martell JM, Verner JJ, Incavo SJ. Clinical performance of a highly cross-linked polyethylene at two years in total hip arthroplasty: a randomized prospective trial. *J Arthroplasty.* 2003;18:55–59.
 92. McCalden RW, MacDonald SJ, Rorabeck CH, Bourne RB, Chess DG, Charron KD. Wear rate of highly cross-linked polyethylene in total hip arthroplasty: a randomized controlled trial. *J Bone Joint Surg Am.* 2009;91:773–782.
 93. McGovern TF, Ammeen DJ, Collier JP, Currier BH, Engh GA. Rapid polyethylene failure of unicondylar tibial components sterilized with gamma irradiation in air and implanted after a long shelf life. *J Bone Joint Surg Am.* 2002;84:901–906.
 94. McKee GK, Watson-Farrar J. Replacement of arthritic hips by the McKee-Farrar prosthesis. *J Bone Joint Surg Br.* 1966;48:245–259.
 95. 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.
 96. 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 simulator. *J Orthop Res.* 1999;17:329–339.
 97. McNulty D, Swope S. The effect of crosslinking UHMWPE on in-vitro wear rates of fixed and mobile bearing knees. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Cross-linked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements.* West Conshohocken, PA: American Society for Testing and Materials; 2004.
 98. Medel F, Kurtz SM, Klein G, Levine H, Sharkey P, Austin M, Kraay M, Rimnac CM. Clinical, surface damage and oxidative performance of Poly II tibial inserts after long-term implantation. *J Long Term Eff Med Implants.* 2008;18:151–165.
 99. Minoda Y, Aihara M, Sakawa A, Fukuoka S, Hayakawa K, Tomita M, Umeda N, Ohzono K. Comparison between highly cross-linked and conventional polyethylene in total knee arthroplasty. *Knee.* 2009;16:348–351.
 100. Miyanishi K, Hara T, Kaminomachi S, Maekawa M, Iwamoto M, Torisu T. Short-term wear of Japanese highly cross-linked polyethylene in cementless THA. *Arch Orthop Trauma Surg.* 2008;128:995–1000.
 101. Moore KD, Beck PR, Petersen DW, Cuckler JM, Lemons JE, Eberhardt AW. Early failure of a cross-linked polyethylene acetabular liner: a case report. *J Bone Joint Surg Am.* 2008;90:2499–2504.
 102. Mu Z, Tian J, Wu T, Yang J, Pei F. A systematic review of radiological outcomes of highly cross-linked polyethylene versus conventional polyethylene in total hip arthroplasty. *Int Orthop.* 2009;33:599–604.
 103. Muratoglu OK, Bragdon CR, O'Connor DO, Jasty M, Harris WH. A novel method of cross-linking ultra-high-molecular-weight polyethylene to improve wear, reduce oxidation, and retain mechanical properties. Recipient of the 1999 HAP Paul Award. *J Arthroplasty.* 2001;16:149–160.
 104. Mutimer J, Devane PA, Adams K, Horne JG. Highly crosslinked polyethylene reduces wear in total hip arthroplasty at 5 years. *Clin Orthop Relat Res.* 2010;468:3228–3233.
 105. Nair PD. Currently practised sterilization methods—some inadvertent consequences. *J Biomater Appl.* 1995;10:121–135.
 106. Nakahara I, Nakamura N, Nishii T, Miki H, Sakai T, Sugano N. Minimum five-year follow-up wear measurement of longevity highly cross-linked polyethylene cup against cobalt-chromium or zirconia heads. *J Arthroplasty.* 2010;25:1182–1187.
 107. Nizard RS, Sedel L, Christel P, Meunier A, Soudry M, Witvoet J. Ten-year survivorship of cemented ceramic-ceramic total hip prosthesis. *Clin Orthop Relat Res.* 1992;282:53–63.
 108. Olyslaegers C, Defoort K, Simon JP, Vandenbergh L. Wear in conventional and highly cross-linked polyethylene cups: a 5-year follow-up study. *J Arthroplasty.* 2008;23:489–494.
 109. Oonishi H, Clarke IC, Masuda S, Amino H. Study of retrieved acetabular sockets made from high-dose, cross-linked polyethylene. *J Arthroplasty.* 2001;16:129–133.
 110. Oonishi H, Kim SC, Takao Y, Kyomoto M, Iwamoto M, Ueno M. Wear of highly cross-linked polyethylene acetabular cup in Japan. *J Arthroplasty.* 2006;21:944–949.
 111. Oonishi H, Takayama Y, Tsuji E. Improvement of polyethylene by irradiation in artificial joints. *Rad Phys Chem.* 1992;39:495–504.
 112. Oral E, Wannomae KK, Hawkins N, Harris WH, Muratoglu OK. Alpha-tocopherol-doped irradiated UHMWPE for high fatigue resistance and low wear. *Biomaterials.* 2004;25:5515–5522.
 113. Premnath V, Harris WH, Jasty M, Merrill EW. Gamma sterilization of UHMWPE articular implants: an analysis of the oxidation problem. *Biomaterials.* 1996;17:1741–1753.
 114. Rajadhyaksha AD, Brotea C, Cheung Y, Kuhn C, Ramakrishnan R, Zelicof SB. Five-year comparative study of highly cross-linked (Crossfire) and traditional polyethylene. *J Arthroplasty.* 2009;24:161–167.
 115. Ramani K, Parasnis NC. Process-induced effects in compression molding of ultra-high molecular weight polyethylene (UHMWPE). In: Gsell RA, Stein HL, Ploskonka JJ, eds. *Characterization and Properties of Ultra-High Molecular Weight Polyethylene.* West Conshohocken, PA: American Society for Testing and Materials; 1998:5–23.
 116. Reeves EA, Barton DC, FitzPatrick DP, Fisher J. Comparison of gas plasma and gamma irradiation in air sterilization on the delamination wear of the ultra-high molecular weight polyethylene used in knee replacements. *Proc Inst Mech Eng H.* 2000;214:249–255.
 117. Ries MD, Weaver K, Beals N. Safety and efficacy of ethylene oxide sterilized polyethylene in total knee arthroplasty. *Clin Orthop Relat Res.* 1996;331:159–163.
 118. Ries MD, Weaver K, Rose RM, Gunther J, Sauer W, Beals N. Fatigue strength of polyethylene after sterilization by gamma irradiation or ethylene oxide. *Clin Orthop Relat Res.* 1996;333:87–95.
 119. Rimnac CM, Klein RW, Betts F, Wright TM. Post-irradiation aging of ultra-high molecular weight polyethylene. *J Bone Joint Surg Am.* 1994;76:1052–1056.
 120. Ring PA. Complete replacement arthroplasty of the hip by the ring prosthesis. *J Bone Joint Surg Br.* 1968;50:720–731.
 121. Rohrl S, Nivbrant B, Minggao L, Hewitt B. In vivo wear and migration of highly cross-linked polyethylene cups a radiostereometry analysis study. *J Arthroplasty.* 2005;20:409–413.
 122. Rohrl SM, Li MG, Nilsson KG, Nivbrant B. Very low wear of non-remelted highly cross-linked polyethylene cups: an RSA study lasting up to 6 years. *Acta Orthop.* 2007;78:739–745.

123. Schmalzried TP, Jasty M, Harris WH. Periprosthetic bone loss in total hip arthroplasty: the concept of effective joint space. *J Bone Joint Surg Am.* 1992;74:849–863.
124. Schmidt MB, Hamilton JV. The effects of calcium stearate on the properties of UHMWPE. *Trans Orthop Res Soc.* 1996;21:22.
125. Scott DL, Campbell PA, McClung CD, Schmalzried TP. Factors contributing to rapid wear and osteolysis in hips with modular acetabular bearings made of hylamer. *J Arthroplasty.* 2000;15:35–46.
126. Sedel L, Kerboul L, Christel P, Meunier A, Witvoet J. Alumina-on-alumina hip replacement: results and survivorship in young patients. *J Bone Joint Surg Br.* 1990;72:658–663.
127. Shia DS, Clohisy JC, Schinsky MF, Martell JM, Maloney WJ. THA with highly cross-linked polyethylene in patients 50 years or younger. *Clin Orthop Relat Res.* 2009;467:2059–2065.
128. Streicher RM. Ionizing irradiation for sterilization and modification of high molecular weight polyethylenes. *Plast Rubber Proc Appl.* 1988;10:221–229.
129. Sutula LC, Collier JP, Saum KA, Currier BH, Currier JH, Sanford WM, Mayor MB, Wooding RE, Sperling DK, Williams IR, Kasprzak DJ, Suprenant VA. Impact of gamma sterilization on clinical performance of polyethylene in the hip. *Clin Orthop Relat Res.* 1995;319:28–40.
130. Swarts D, Gsell R, King R, Devanathan D, Wallace S, Lin S, Rohr W. Aging of calcium stearate-free polyethylene. In: *Transactions of the 5th World Biomaterials Congress.* Mount Laurel, NJ: Society for Biomaterials; 1996:196.
131. Tower SS, Currier JH, Currier BH, Lyford KA, Van Citters DW, Mayor MB. Rim cracking of the cross-linked longevity polyethylene acetabular liner after total hip arthroplasty. *J Bone Joint Surg Am.* 2007;89:2212–2217.
132. Triclot P, Grosjean G, El Masri F, Courpied JP, Hamadouche M. A comparison of the penetration rate of two polyethylene acetabular liners of different levels of cross-linking: a prospective randomised trial. *J Bone Joint Surg Br.* 2007;89:1439–1445.
133. Wang A, Essner A, Polineni VK, Stark C, Dumbleton JH. Lubrication and wear of ultra-high molecular weight polyethylene in total joint replacements. *Tribol Int.* 1998;31:17–33.
134. Wang A, Manley M, Serekian P. Wear and structural fatigue simulation of crosslinked ultra-high molecular weight polyethylene for hip and knee bearing applications. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Crosslinked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements.* West Conshohocken, PA: American Society for Testing and Materials; 2004.
135. Waugh W. *John Charnley: The Man and the Hip.* London, UK: Springer-Verlag; 1990.
136. White SE, Paxson RD, Tanner MG, Whiteside LA. Effects of sterilization on wear in total knee arthroplasty. *Clin Orthop Relat Res.* 1996;331:164–171.
137. Whittaker JP, Charron KD, McCalden RW, Macdonald SJ, Bourne RB. Comparison of steady state femoral head penetration rates between two highly cross-linked polyethylenes in total hip arthroplasty. *J Arthroplasty.* 2010;25:680–686.
138. Willert HG, Bertram H, Buchhorn GH. Osteolysis in alloarthroplasty of the hip: the role of ultra-high molecular weight polyethylene wear particles. *Clin Orthop Relat Res.* 1990;258:95–107.
139. Willert HG, Buchhorn GH, Eyerer P. *Ultra-high Molecular Weight Polyethylene as Biomaterial in Orthopedic Surgery.* Toronto, Canada: Hogrefe & Huber Publishers; 1991.
140. Williams IR, Mayor MB, Collier JP. The impact of sterilization method on wear in knee arthroplasty. *Clin Orthop Relat Res.* 1998;356:170–180.
141. Winter M, Griss P, Scheller G, Moser T. Ten- to 14-year results of a ceramic hip prosthesis. *Clin Orthop Relat Res.* 1992;282:73–80.
142. Wright TM, Bartel DL. The problem of surface damage in polyethylene total knee components. *Clin Orthop Relat Res.* 1986;205:67–74.
143. Wright TM, Fukubayashi T, Burstein AH. The effect of carbon fiber reinforcement on contact area, contact pressure, and time-dependent deformation in polyethylene tibial components. *J Biomed Mater Res.* 1981;15:719–730.
144. Wroblewski BM, Siney PD, Dowson D, Collins SN. Prospective clinical and joint simulator studies of a new total hip arthroplasty using alumina ceramic heads and cross-linked polyethylene cups. *J Bone Joint Surg Br.* 1996;78:280–285.
145. Wrona M, Mayor MB, Collier JP, Jensen RE. The correlation between fusion defects and damage in tibial polyethylene bearings. *Clin Orthop Relat Res.* 1994;299:92–103.
146. Yao JQ, Lu MP, Johnson TS, Gilbertson LN, Swarts D, Blanchard CR, Crowninshield RD. Improved resistance to wear, delamination and posterior loading fatigue damage of electron beam irradiated, melt-annealed, highly crosslinked UHMWPE knee inserts. In: Kurtz SM, Gsell R, Martell J, eds. ASTM STP 1445. *Highly Crosslinked and Thermally Treated Ultra-High Molecular Weight Polyethylene For Joint Replacements.* West Conshohocken, PA: American Society for Testing and Materials; 2004.