HSSJ (2013) 9:264–269
DOI 10.1007/s11420-013-9352-x

HOSPITAL FOR SPECIAL SURGERY

REVIEW ARTICLE

Highly Cross-Linked Polyethylene May Not Have an Advantage in Total Knee Arthroplasty

Vasileios I. Sakellariou, MD, PhD · Peter Sculco, MD · Lazaros Poultsides, MD, PhD · Timothy Wright, PhD · Thomas P. Sculco, MD

Received: 21 May 2013/Accepted: 16 July 2013 / Published online: 10 August 2013

Abstract *Background:* Long-term results after total knee replacement (TKR) with conventional and compression-molded polyethylene (PE) have been excellent. The introduction of highly cross-linked polyethylene (XLPE), which has demonstrated superior wear properties in total hip replacement (THR), has led to its recent use in TKR. However, the knee has a unique biomechanical environment characterized by large contact stresses and shear forces and differs from the highly conforming articulation (and primarily abrasive and adhesive wear) found in THR. For this reason, XLPE, with its decreased fatigue resistance and toughness compared to PE, may not be the best material to withstand these unique forces. *Questions:* This review and evaluation of the literature aims to answer the following questions. What are the advantages and disadvantages of XLPE in TKR? Does its success in THR ensure a favorable outcome in TKR? Does the increased cost of XLPE justify its use in TKR? *Methods:* A systematic literature review of MEDLINE, Science Direct, and Google Scholar databases was performed searching for advantages and disadvantages of XLPE in TKR. We found 18 biomechanical in vitro investigations and 3 clinical studies comparing conventional and XLPEs. We included levels I through IV published articles in peer-reviewed journals in English language. *Results:* Several in vitro studies found XLPE to have significantly better wear properties compared to conventional PE. However, the two clinical investigations that directly compared conventional PE and XLPE found no difference in clinical or radiographic outcomes. Additionally, clinical studies with long-term follow-up on TKR with conventional PE did not find wear-induced osteolysis to be a major cause of failure. Four studies did find cost to be significantly higher for XLPE compared to conventional PE. *Conclusions:* Based on our review, we concluded that (1) the material properties of XLPE reduce adhesive and abrasive wear, but not the risk of crack propagation, deformation, pitting, and delamination found in TKR; (2) wear-induced osteolysis in TKR has not been found to be a major cause of failure at long-term follow-up; (3) mid-term follow-up studies show no difference in any recorded outcome measure between conventional PE and XLPE; and (4) XLPE is two to four times the cost of conventional PE without an improvement in clinical or radiographic outcomes. For these reasons, we currently cannot recommend the use of XLPE in TKR. Conventional compression-molded polyethylene with its outstanding long-term results should remain the material of choice in TKR.

Keywords cross-linked · polyethylene · total knee replacement · annealed · remelted · radiation · crack · compression molded

Work performed at Hospital for Special Surgery, 535 East 70th Street, New York, NY, 10021, USA

Electronic supplementary material The online version of this article (doi:10.1007/s11420-013-9352-x) contains supplementary material, which is available to authorized users.

V. I. Sakellariou, MD, PhD (✉) · P. Sculco, MD ·
L. Poultsides, MD, PhD · T. Wright, PhD · T. P. Sculco, MD
Hospital for Special Surgery,
535 East 70th street,
New York, NY 10021, USA
e-mail: SakellariouV@hss.edu; b_sakellariou@yahoo.com

Introduction

Total knee replacement (TKR) is a successful treatment for disabling knee arthritis, and many studies document the outstanding long-term results with first- and second-generation implant designs [31, 49, 50]. Ultrahigh molecular weight polyethylene (UHMWPE) remains the gold standard bearing surface for the tibial and patellar components. Improvements in wear characteristics and mechanical properties of UHMWPE have been made since the original

polyethylene used in TKR. The UHMWPE initially used in these implants was compression molded followed by conventional gamma irradiation-in-air polyethylene (PE). Compression molding enhanced wear properties and longevity [20, 54]. However, two setbacks in the development of UHMWPE included use of carbon fiber reinforcement (Poly II, Zimmer, Warsaw, IN, USA) and use of highly crystalline UHMWPE (Hylamer, DePuy DuPont, Warsaw, IN, USA), which both failed clinically despite preclinical in vitro testing demonstrating their safety and effectiveness [2, 32, 41].

Cross-linked polyethylene (XLPE) is a modified form of UHMWPE that has higher cross-link density achieved by irradiation beyond that necessary for sterilization and thermal treatment [27]. Gamma (γ) or electron beam irradiation breaks intermolecular bonds and generates free radicals that promote cross-linking across multiple polymer chains and increases the PE density. However, reactions of the residual free radicals with oxygen in an ambient environment induce a reduction in the molecular weight of the PE that compromises its mechanical properties. Post-irradiation thermal treatments have been devised to reduce the concentration of residual free radicals and enhance oxidative stability. With remelting, the crystalline structure of PE is converted to the amorphous phase, thus allowing the recombination and elimination of free radicals and significant improvement of the oxidative stability and resistance to abrasive and adhesive wear [11, 46]. However, remelting reduces crystallinity, adversely affecting mechanical properties including fatigue strength. Conversely, annealing at temperatures below the melting point preserves the mechanical properties, but leaves behind residual free radicals and thus the potential for increased oxidation in vivo after implantation [11, 39].

Second-generation XLPE is produced by two methods: thermal treatment (consisting of sequential irradiation and annealing) or by anti-oxidant agents (vitamin E), both of which eliminate the remelting process while maintaining oxidative resistance [7, 35, 44, 48]. The method of final sterilization and packaging is also important, since late oxidation of XLPE may occur in the presence of oxygen [29, 32, 33].

Several biomechanical and clinical studies comparing XLPE and conventional PE in total hip replacement (THR) found XLPE results in a significant reduction in abrasive and adhesive wear [12–14]. Midterm clinical follow-up studies show minimal bearing surface wear of ~0.01 mm/year and no radiographic evidence of osteolysis at 10 years [11, 51]. The superior performance of XLPE in THR has led to its use in TKR. However, the unique biomechanical environment seen in TKR, characterized mainly by larger contact stresses and shear forces, differs from the highly conforming articulation and primarily abrasive and adhesive wear found in THR. For this reason, XLPE, with its decrease fatigue resistance and toughness compared to PE, may not be the best material to withstand these unique forces.

With this controversy in mind, we conducted a systematic review of the literature to address the following questions: (1) what are the advantages and disadvantages of highly cross-linked polyethylene?; (2) does its success in THR indicate a similar favorable outcome in TKR?; and (3) does the increased cost of XLPE justify its use in TKR?

Search Strategy and Criteria

We conducted an extensive review of the English-language literature using the MEDLINE, ScienceDirect, EMBASE, and Google Scholar databases and identified all relevant publications referencing the use of XLPE in TKR. Title and abstract fields were queried using the following search terms with the limit "English language": cross*link*[Title/Abstract] OR crosslink*[Title/Abstract] AND polyethylene[Title/Abstract] OR UHMWPE[Title/Abstract] OR UHMW*PE[Title/Abstract] OR "XLPE"[Title/Abstract] OR "Aeonian"[Title/Abstract] OR "Crossfire"[Title/Abstract] OR "Marathon"[Title/Abstract] OR "Longevity"[Title/Abstract] OR "Prolong"[Title/Abstract] OR "Durasul"[Title/Abstract] "vitamin E"[Title/Abstract] OR "E-Poly"[Title/Abstract] OR "X3"[Title/Abstract] "AND (knee) AND (wear OR osteolysis OR fatigue OR fracture OR penetration OR delamination OR pitting)" OR (cost OR effectiveness) AND "2001/1/1 to current"[Publication Date] AND English [Language]. Original search revealed 374 entries. After reviewing titles and abstracts and excluding 152 duplicate entries, 124 entries reporting on hip arthroplasties, 17 studies published in languages other than English and 40 irrelevant articles, we ended up with 41 studies for our review.

We identified 18 papers that presented experimental analyses of the biomechanical properties of the XLPE [3–5, 10, 11, 17–19, 21, 26, 28, 29, 35–39, 46, 48, 52–54]. Five compared the resistance to crack initiation and propagation between XLPE and conventional compression molded PE [18, 19, 21, 42, 48]. Eight studies reported on the improved wear resistance in second-generation XLPE, particularly with the addition of antioxidants (vitamin E) [1, 7, 9, 15, 24, 28, 44, 45]. Three focused on retrieval analyses [8, 9, 40]. Only three papers reported on the clinical outcome of XLPE in TKR [25, 30, 34]. Two case reports showing early failure of the patellar component were included in a separate category [23, 53]. One group of authors suggested that the smaller diameter wear particles produced by XLPE may have different biological reactivity [17]. Four studies directly or indirectly discussed cost [6, 7, 22, 51].

Results

What are the Advantages and Disadvantages of Highly Cross-Linked Polyethylene and Does Its Success in THR Ensure a Favorable Outcome in TKR?

Cross-linking improves wear resistance of the bearing surface over that of conventional UHMWPE. However, this process generates free radicals, which induce oxidative degradation of the polymer through a reduction of its molecular weight that compromise its mechanical properties and long-term performance [27, 29]. This is prevented by a post-irradiation thermal treatment of the PE, which enhances its oxidative stability [29, 39]. Thermal treatment and the process of terminal sterilization and packaging is also a variable that may affect long-term performance of different XLPEs in vivo [21].

The femoro-acetabular articulation in a THR is a highly conforming ball–socket joint that produces characteristic abrasive and adhesive bearing surface wear [43, 54]. In

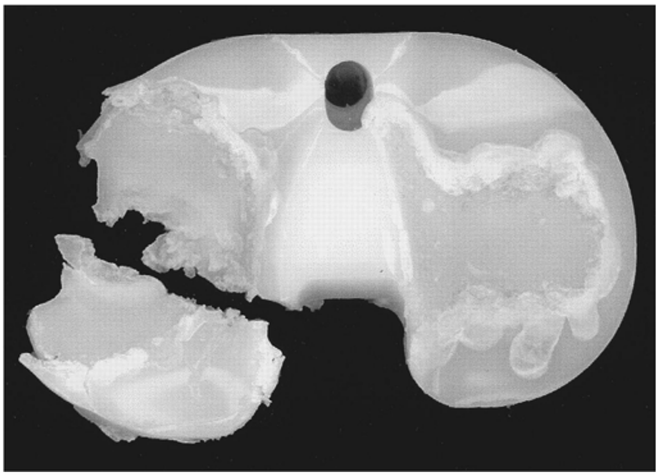

Fig. 1. Retrieval of a highly cross-linked polyethylene that shows gross damage of the tibial component.

contrast, the femorotibial articulation of a TKR, with its sliding and rolling motions, is less conforming and creates shear and contact stresses not seen in the hip. Tensile stress near the edges of the PE insert and subsurface shear stress along the articulating contact area produces pitting and delamination, a type of PE wear found specifically in TKR. In addition, the cyclic motion of the knee creates residual stresses that contribute to fatigue and failure [20].

Due to the low conformity and small contact area of the femoral component on the tibial PE, peak contact stresses during activities of daily living may exceed the yield strength of PE (18–20 MPa) [16, 54]. These excessive forces may result in plastic deformation and consequently alter surface geometry and negatively affect alignment and stability. Altered load distribution between medial and lateral plateaus may then produce even more PE wear. XLPE with its decreased toughness, ductility, and resistance to fatigue makes it more susceptible to failure under these conditions [29].

Compression-molded PE undergoes irradiation at a lower level than XLPE (2.5–4 vs 5–10 mrad). At this radiation dose, conventional PE undergoes some cross-linking without significantly altering its mechanical properties or yield strength [54]. Burnishing, delamination, and pitting are the types of wear found in conventional PE implants [16, 38, 54]. In contrast, XLPE shows gross damage from focal increased loads commonly around the tibial intercondylar post and peripheral PE margin [16, 20, 52]. In the most severe cases fracture of the tibial post and PE plateau have been documented. The decreased fatigue strength and ductility of XLPE increase its susceptibility to such types of failure (Figs. 1 and 2).

Two clinical studies directly compare clinical and radiographic outcomes between conventional PE to XLPE in TKR. Hodrick et al. compared gamma-inert-sterilized PE to Durasul® XLPE in a cruciate retaining (CR) knee design (Natural Knee®, Zimmer) with the rate of revision as the primary outcome measure [25]. One hundred cases in each group at a mean follow-up of 7.6 years for conventional PE and 6.3 years for XLPE showed no significant difference in rate of revision. In the second clinical trial, 89 TKRs using NexGen® CR implants with Prolong® (Zimmer) XLPE were compared to 113 knees using NexGen® CR with a conventional PE insert [34]. At short-term follow-up of 2 years, there were no revisions or radiographic evidence of osteolysis. Clinical outcomes were similar with no significant difference in Knee Society Score and ROM.

Does the Increased Cost of XLPE Justify Its Use in TKR?

First- and second-generation XLPE costs two to four times as much as conventional compression molded PE [6, 22]. Gioe et al. compared 3,462 "standard" TKRs to 2,806 "premium" TKRs (including XLPE inserts in the premium group) and documented that the premium implants were more expensive (by up to $1,000) without a difference in the cumulative revision rate at 7–8 years [22]. Other reports showed no difference in clinical function or survival in XLPE compared to lower cost conventional PE [31, 47, 49, 50].

Discussion

We performed a comprehensive literature search of both biomechanical and clinical studies assessing the advantages

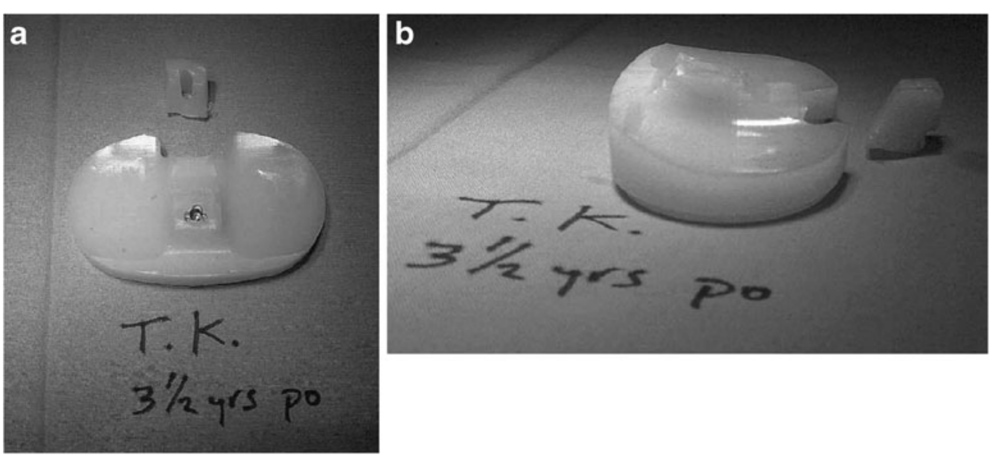

Fig. 2. Retrieval of a highly cross-linked polyethylene from a posterior stabilized (PS) knee design that demonstrates a broken tibial post. **a** Superior view of the fractured post and insert. **b** Lateral view of the fractured post and insert.

and disadvantages of XLPE versus conventional PE in TKR. Our secondary goal, based on these findings, was to determine if the increased cost of XLPE is justified.

Our systematic review of the literature has limitations. There are several studies on first generation XLPE while the literature on vitamin E infused second-generation XLPE is limited and, for this reason, the current review focuses on first generation XLPE. Differences in the type of PE resin, radiation dose, and postradiation thermal treatment produce XLPEs with different physical and mechanical properties, making interstudy comparisons difficult. In addition, clinical outcomes of XLPE in TKR are limited to short- and mid-term follow-up time periods. The cost of first and second generation XLPE is difficult to calculate because the femoral and tibial components are included in the cost analyses of most studies. While not a formal meta-analysis and despite these limitations, this paper provides a systematic review of the literature discussing the use of XLPE versus conventional PE in TKR.

Biomechanical testing of XLPE, while extensively studied, lacks homogeneity. A lack of uniform testing conditions makes it difficult to compare XLPE across experimental studies [11, 27, 47]. Biomechanical testing on knee simulators may not accurately reproduce native joint motion because knee kinematics consists of a complex interplay of rolling, sliding, and rotation that is difficult to imitate in vitro [11, 30, 54]. Interstudy variations in cumulative load and total number of cycles (per million) may affect wear patterns and make it difficult to compare XLPE performance [30]. The current literature on biomechanics in hip and knee simulators measures abrasive and adhesive wear rather than delamination and pitting, which prioritizes the wear pattern found in the hip rather than the knee [30, 36, 37]. These in vitro simulator studies may overestimate the recorded reduction in PE wear since the testing conditions assume optimal alignment and ligament balance and a lack of third body wear (i.e., bony particles, cement, etc.) [16, 29, 30]. For all these reasons, biomechanical in vitro simulation data and its proposed benefits in vivo should be met with caution.

The evolution of PE includes several designs with reported in vitro success but resulted in catastrophic clinical failures. Two such examples are the Poly II (PE with carbon fibers) and Hylamer (PE gamma irradiated in air), which both excelled in biomechanical testing but failed clinically [2, 20, 41]. These recent PE failures suggest that purported design benefits should be critically evaluated and met with caution before widespread in vivo implementation.

With each gait cycle, the PE insert must withstand the biomechanical environment of a total knee replacement, which includes peripheral contact and subsurface shear stress and significant forces against the tibial post. Cross-linking of PE, which improves resistance to adhesive and abrasive wear, decreases the toughness, ductility, and resistance to fatigue, which may lead to eventual failure of the PE. The increased "brittleness" of the XLPE in TKR makes it a higher risk for crack propagation and component failure. For this reason, ideal cross-linking for PE in TKR should be less than in THR and "moderately-crossed-linked polyethylenes" may be best suited for a TKR [10, 29, 30]. Reduced cross-linking requires a decrease in radiation dosage and should not exceed 7.5 mrad if "moderately" cross-linked PE is desired [30]. In order to maintain ductility and toughness during cross-linking, sequential annealing, which includes multiple sessions of irradiation and annealing, is preferred to a single session of post-irradiation treatment [15, 27, 30, 35]. Other types of second-generation XLPEs use the antioxidant vitamin E in order to reduce residual free radicals after irradiation. Vitamin E is added to PE in two ways: (1) by diffusion in which vitamin E is blended with PE powder or (2) by the addition of vitamin E after radiation and cross-linking. Moderately crossed-linked second-generation XLPE has the theoretical benefits of maintained toughness and fatigue resistance combined with superior resistance to adhesive and abrasive wear. However, short-term follow-up has yet to demonstrate a clinical benefit. In addition, second-generation XLPE may produce secondary negative effects of unknown significance. For example, the intra-articular and systemic effects of higher vitamin E XLPE dosages are unknown [1, 7, 20, 24, 28, 44, 45]. And while XLPE clearly demonstrates a reduction in the number of wear particles produced in vitro, the submicron (<0.15 μm) particle size may increase biologic response and stimulate a more aggressive macrophage and osteoclast reaction [47, 52]. Whether this will produce clinically significant periprosthetic osteolysis is unknown and has not been documented at short-term follow-up [7, 32, 52].

Long-term clinical data demonstrates excellent performance of compression molded PE. A recent publication on the monoblock compression molded tibial PE insert in young patients reported implant survivorship of over 90% at 20 years [49]. The authors concluded that this should be viewed as an expectation and benchmark for component performance in the future.

Clinical studies comparing XLPE with the conventional PE are limited [25, 34]. One study with 2-year follow-up found no significant difference in any outcome measure between XLPE and conventional compression molded PE [34]. Early retrieval studies demonstrate no difference in either articular or backside surface damage scores [17, 27, 46]. In addition, the use of XLPE in posterior stabilized and constrained condylar knee designs should be limited until it has been shown to withstand the accumulated stresses across the tibial post without evidence of failure [25, 30, 47, 52]. Other areas of high shear stress have resulted XLPE failures included the pegs of the patella component [23, 53].

The current literature on XLPE does not support its use as a cost-effective implant. While two to four times the cost of conventional PE, the increased cost of XLPE is rarely reported in the literature. Most studies that report a cost-based analysis of XLPE in THR include acetabular and femoral components and make it difficult to isolate the contribution of XLPE to the total cost. Moreover, it has to be mentioned that implants reported as "premium" include a wide variety of bearing and implant designs (i.e., mobile bearing, high flexion designs, and oxidized zirconium implants) making findings regarding the cost effectiveness of each one inconclusive and probably misleading. In the current era of cost containment, premium pricing of XLPE compared to conventional PE would be hard

to justify without evidence of improved survival or clinical benefit. Until longer-term follow-up studies are available, XLPE should be considered an expensive technology and limited to a cohort of younger individuals who may benefit from the theoretical advantages of second-generation "moderately" crossed-linked XLPE.

In summary, based on the current literature, the benefit of XLPE in TKR is unknown. Biomechanical testing of XLPE in vitro has been shown to be superior but translation to the in vivo biomechanical environment of the knee may produce inferior results. Second-generation XLPE has made progress in balancing the competing priorities of resistance to abrasive and adhesive wear while maintaining the resistance to fatigue required in TKR PE. Whether these recent advances in second-generation XLPE will produce clinical and radiographic benefits has yet to be seen at short-term follow-up. The current excellent performance of conventional PE in TKR establishes a benchmark for comparison and further studies comparing the use of XLPE and conventional PE with longer-term follow-up are required before the increased cost of XLPE can be justified. Until then, the authors support the limited use of XLPE in a younger patient population and recommend continued use of conventional PE as the implant material of choice in patients undergoing TKR.

Disclosures

Conflict of Interest: Vasileios I. Sakellariou, MD, PhD; Peter Sculco, MD; and Lazaros Poultsides, MD, PhD have declared that they have no conflict of interest. Timothy Wright, PhD receives royalties from Mathys AB, stock options from Exactech, editorial honorarium from Orthopaedic Research Society, and grants from Stryker (outside the work). Thomas P. Sculco, MD receives payment as a board member of HSS Board of Trustees (outside the work).

Human/Animal Rights: This article does not contain any studies with human or animal subjects performed by any of the authors.

Informed Consent: Not applicable.

Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

References

1. Affatato S, Bracco P, Costa L, Villa T, Quaglini V, Toni A. In vitro wear performance of standard, crosslinked, and vitamin-E-blended UHMWPE. *J Biomed Materials Res Part A*. 2012; 100: 554-560.
2. Ahn NU, Nallamshetty L, Ahn UM, et al. Early failure associated with the use of Hylamer-M spacers in three primary AMK total knee arthroplasties. *J Arthroplast*. 2001; 16: 136-139.
3. Akagi M, Asano T, Clarke IC, et al. Wear and toughness of crosslinked polyethylene for total knee replacements: a study using a simulator and small-punch testing. *J Orthop Res*. 2006; 24: 2021-2027.
4. Asano T, Akagi M, Clarke IC, Masuda S, Ishii T, Nakamura T. Dose effects of cross-linking polyethylene for total knee arthroplasty on wear performance and mechanical properties. *J Biomed Materials Res Part B*. 2007; 83: 615-622.
5. Baker DA, Bellare A, Pruitt L. The effects of degree of crosslinking on the fatigue crack initiation and propagation resistance of orthopedic-grade polyethylene. *J Biomed Materials Res Part A*. 2003; 66: 146-154.
6. Bozic KJ, Morshed S, Silverstein MD, Rubash HE, Kahn JG. Use of cost-effectiveness analysis to evaluate new technologies in orthopaedics. The case of alternative bearing surfaces in total hip arthroplasty. *J Bone Joint Surg Am vol*. 2006; 88: 706-714.
7. Bracco P, Oral E. Vitamin E-stabilized UHMWPE for total joint implants: a review. *Clin Orthop Relat Res*. 2011; 469: 2286-2293.
8. Bradford L, Baker D, Ries MD, Pruitt LA. Fatigue crack propagation resistance of highly crosslinked polyethylene. *Clin Orthop Relat Res*. 2004; 429: 68-72.
9. Bradford L, Baker DA, Graham J, Chawan A, Ries MD, Pruitt LA. Wear and surface cracking in early retrieved highly cross-linked polyethylene acetabular liners. *J Bone Joint Surg Am vol*. 2004; 86-A: 1271-1282.
10. Brockett CL, Jennings LM, Hardaker C, Fisher J. Wear of moderately cross-linked polyethylene in fixed-bearing total knee replacements. *Proc Inst Mech Eng Part H, J Eng Med*. 2012; 226: 529-535.
11. Collier JP, Currier BH, Kennedy FE, et al. Comparison of cross-linked polyethylene materials for orthopaedic applications. *Clin Orthop Relat Res*. 2003; 414: 289-304.
12. D'Antonio JA, Manley MT, Capello WN, et al. Five-year experience with crossfire highly cross-linked polyethylene. *Clin Orthop Relat Res*. 2005; 441: 143-150.
13. Digas G, Karrholm J, Thanner J, Malchau H, Herberts P. Highly cross-linked polyethylene in cemented THA: randomized study of 61 hips. *Clin Orthop Relat*. 2003; 417: 126-138.
14. Digas G, Karrholm J, Thanner J, Malchau H, Herberts P. The Otto Aufranc Award. 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.
15. 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.
16. Fisher J, Jennings LM, Galvin AL, Jin ZM, Stone MH, Ingham E. 2009 Knee Society Presidential Guest Lecture: polyethylene wear in total knees. *Clin Orthop Relat Res*. 2010; 468: 12-18.
17. Fisher J, McEwen HM, Tipper JL, et al. Wear, debris, and biologic activity of cross-linked polyethylene in the knee: benefits and potential concerns. *Clin Orthop Relat Res*. 2004; 428: 114-119.
18. Furmanski J, Gupta S, Chawan A, et al. Aspherical femoral head with highly cross-linked ultra-high molecular weight polyethylene surface cracking. A case report. *J Bone Joint surg Am Vol*. 2007; 89: 2266-2270.
19. Furmanski J, Rimnac CM. Crack propagation resistance is similar under static and cyclic loading in crosslinked UHMWPE: a pilot study. *Clin Orthop Relat Res*. 2011; 469: 2302-2307.
20. Gee AO, Lee GC. Alternative bearings in total knee arthroplasty. *Am J Orthop (Belle Mead NJ)*. 2012; 41: 280-283.
21. Gencur SJ, Rimnac CM, Kurtz SM. Fatigue crack propagation resistance of virgin and highly crosslinked, thermally treated ultra-high molecular weight polyethylene. *Biomaterials*. 2006; 27: 1550-1557.
22. 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.
23. Goldstein MJ, Ast MP, Dimaio FR. Acute posttraumatic catastrophic failure of a second-generation, highly cross-linked ultra-high-molecular-weight polyethylene patellar component. *Orthopedics*. 2012; 35: e1119-1121.
24. Haider H, Weisenburger JN, Kurtz SM, et al. Does vitamin E-stabilized ultrahigh-molecular-weight polyethylene address concerns of cross-linked polyethylene in total knee arthroplasty? *J Arthroplast*. 2012; 27: 461-469.
25. 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.
26. Huot JC, Van Citters DW, Currier JH, Currier BH, Mayor MB, Collier JP. Evaluating the suitability of highly cross-linked and

remelted materials for use in posterior stabilized knees. *J Biomed Materials Res Part B, Applied Biomaterials*. 2010; 95: 298-307.
27. Jasty M, Rubash HE, Muratoglu O. Highly cross-linked polyethylene: the debate is over—in the affirmative. *J Arthroplast*. 2005; 20: 55-58.
28. Kurtz SM, Dumbleton J, Siskey RS, Wang A, Manley M. Trace concentrations of vitamin E protect radiation crosslinked UHMWPE from oxidative degradation. *J Biomed Materials Res Part A*. 2009; 90: 549-563.
29. Kurtz SM, Gawel HA, Patel JD. History and systematic review of wear and osteolysis outcomes for first-generation highly crosslinked polyethylene. *Clin Orthop Relat Res*. 2011; 469: 2262-2277.
30. Lachiewicz PF, Geyer MR. The use of highly cross-linked polyethylene in total knee arthroplasty. *J Am Acad Orthop Surg*. 2011; 19: 143-151.
31. Ma HM, Lu YC, Ho FY, Huang CH. Long-term results of total condylar knee arthroplasty. *J Arthroplast*. 2005; 20: 580-584.
32. Medel F, Kurtz SM, Klein G, et al. Clinical, surface damage and oxidative performance of poly II tibial inserts after long-term implantation. *J long-term effects Med Imp*. 2008; 18: 151-165.
33. Medel FJ, Kurtz SM, Parvizi J, Klein GR, Kraay MJ, Rimnac CM. In vivo oxidation contributes to delamination but not pitting in polyethylene components for total knee arthroplasty. *J Arthroplast*. 2011; 26: 802-810.
34. Minoda Y, Aihara M, Sakawa A, et al. Comparison between highly cross-linked and conventional polyethylene in total knee arthroplasty. *Knee*. 2009; 16: 348-351.
35. Morrison ML, Jani S. Evaluation of sequentially crosslinked ultra-high molecular weight polyethylene. *J Biomed Materials Res Part B*. 2009; 90: 87-100.
36. Muratoglu OK, Bragdon CR, Jasty M, O'Connor DO, Von Knoch RS, Harris WH. Knee-simulator testing of conventional and cross-linked polyethylene tibial inserts. *J Arthroplast*. 2004; 19: 887-897.
37. Muratoglu OK, Burroughs BR, Bragdon CR, Christensen S, Lozynsky A, Harris WH. Knee simulator wear of polyethylene tibias articulating against explanted rough femoral components. *Clin Orthop Relat Res*. 2004; 428: 108-113.
38. Muratoglu OK, Mark A, Vittetoe DA, Harris WH, Rubash HE. Polyethylene damage in total knees and use of highly crosslinked polyethylene. *J Bone Joint Surg Am Vol*. 2003; 85(A Suppl 1): S7-S13.
39. Muratoglu OK, Merrill EW, Bragdon CR, et al. Effect of radiation, heat, and aging on in vitro wear resistance of polyethylene. *Clin Orthop Relat Res*. 2005; 417: 253-262.
40. Muratoglu OK, Ruberti J, Melotti S, Spiegelberg SH, Greenbaum ES, Harris WH. Optical analysis of surface changes on early retrievals of highly cross-linked and conventional polyethylene tibial inserts. *J Arthroplast*. 2003; 18: 42-47.
41. Norton MR, Yarlagadda R, Anderson GH. Catastrophic failure of the Elite Plus total hip replacement, with a Hylamer acetabulum and zirconia ceramic femoral head. *J Bone J Surg British Vol*. 2002; 84: 631-635.
42. Oral E, Malhi AS, Muratoglu OK. Mechanisms of decrease in fatigue crack propagation resistance in irradiated and melted UHMWPE. *Biomaterials*. 2006; 27: 917-925.
43. Oral E, Malhi AS, Wannomae KK, Muratoglu OK. Highly cross-linked ultrahigh molecular weight polyethylene with improved fatigue resistance for total joint arthroplasty: recipient of the 2006 Hap Paul Award. *J Arthroplast*. 2008; 23: 1037-1044.
44. Oral E, Muratoglu OK. Vitamin E diffused, highly crosslinked UHMWPE: a review. *Int Orthop*. 2011; 35: 215-223.
45. Oral E, Wannomae KK, Rowell SL, Muratoglu OK. Diffusion of vitamin E in ultra-high molecular weight polyethylene. *Biomaterials*. 2007; 28: 5225-5237.
46. Popoola OO, Yao JQ, Johnson TS, Blanchard CR. Wear, delamination, and fatigue resistance of melt-annealed highly crosslinked UHMWPE cruciate-retaining knee inserts under activities of daily living. *J Orthop Res*. 2010; 28: 1120-1126.
47. Ries MD. Highly cross-linked polyethylene: the debate is over—in opposition. *J Arthroplast*. 2005; 20: 59-62.
48. Rimnac C, Pruitt L. How do material properties influence wear and fracture mechanisms? *J Am Acad Orthop Surg*. 2008; 16(Suppl 1): S94-100.
49. Ritter MA. The anatomical graduated component total knee replacement: a long-term evaluation with 20-year survival analysis. *J Bone Joint Surg British Vol*. 2009; 91: 745-749.
50. Ritter MA, Berend ME, Meding JB, Keating EM, Faris PM, Crites BM. Long-term followup of anatomic graduated components posterior cruciate-retaining total knee replacement. *Clin Orthop Relat Res*. 2001; 388: 51-57.
51. 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.
52. Stoller AP, Johnson TS, Popoola OO, Humphrey SM, Blanchard CR. Highly crosslinked polyethylene in posterior-stabilized total knee arthroplasty: in vitro performance evaluation of wear, delamination, and tibial post durability. *J Arthroplast*. 2011; 26: 483-491.
53. Stulberg BN, Wright TM, Stoller AP, Mimnaugh KL, Mason JJ. Bilateral patellar component shear failure of highly cross-linked polyethylene components: report of a case and laboratory analysis of failure mechanisms. *J Arthroplast*. 2012; 27: 789-796.
54. Wright TM. Polyethylene in knee arthroplasty: what is the future? *Clin Orthop Relat Res*. 2005; 440: 141-148.