CHAPTER 2

Ultra-High Molecular Weight Polyethylene in Total Knee Arthroplasty

A. Seth Greenwald and Christine S. Heim

THE PROBLEM

The enduring success of the low-friction arthroplasty, advanced by Sir John Charnley as a solution for hip arthrosis, may be appreciated by the fact that in 2002 almost 700000 primary and revision hip and knee arthroplasties were performed in the United States, a number more than doubling on a global basis[1] (Table 2.1). The prevalence of aseptic loosening attributed to ultra-high molecular weight polyethylene (UHMWPE) wear debris-induced osteolysis is in the single digits in most contemporary knee series, with some reports describing prosthesis survival beyond 20 years.[2–12] Despite this obvious success, UHMWPE wear is an inescapable consequence of total joint articulation and is of contemporary concern particularly as our population grays and lifestyle demands increase.[13–22] Appreciating both the causes and remedies of *in vivo* UHMWPE failure assists the goal of avoiding total knee arthroplasty revision as an endpoint.

THE MATERIAL

The UHMWPE used in joint arthroplasty components results from polymerization of ethylene gas into a fine resin powder of submicron and micron size distribution. A number of resin mixtures exist, but GUR 1050 is the prevalent polymer used in contemporary devices. They are consolidated with the use of ram extrusion or compression-molding techniques. Structurally, UHMWPE is made up of repeating carbon-hydrogen chains that are arranged in ordered (crystalline) and disordered (amorphous) regions.[23]

Processing Shortcomings

Inadequate quality control during manufacture has resulted in fusion defects arising from incomplete polymerization, voids, and foreign body inclusions, which ultimately contribute to the *in vivo* degradation of the final part.[24–26] Previous attempts to improve UHMWPE performance have included carbon fiber reinforcement (Poly-2)[27] and polymer reprocessing by hot isostatic pressing (Hylamer).[28] The former was withdrawn from the market because of an unexpectedly high wear rate[29] (Figure 2-1), while the latter has been linked to debris-induced osteolytic response, especially when sterilized by gamma irradiation in air[30] (Figure 2-2). Heat pressing was yet another attempt to improve the finish of the articular surface, but was associated with UHMWPE fatigue and early delamination[31] (Figure 2-3). These material innovations describe checkered pasts as they moved from the laboratory to clinical application.

Sterilization Oversights

Gamma irradiation in air has, until recently, been the predominant method of UHMWPE component sterilization and, despite current concerns, represents the only gold standard against which contemporary material improvements will be measured over time. However, recent attention drawn to an increasing prevalence of tibial component failures associated with debris-induced osteolysis has raised concerns over the long-term durability of contemporary devices.[32,33] A clinical follow-up study reported by Bohl et al. suggests that this may be accounted for by the prolonged shelf storage prior to implantation of UHMWPE components gamma irradiated in air.[34] A 12% to 20% reduction in *in vivo* survival is noted for shelf storage ranging from 4 to 11 years with a mean *in vivo* time to revision of 2.5 years (Figures 2-4 and 2-5).

TABLE 2.1. Hip and Knee Arthroplasty Procedures Performed in the United States in 2002.

	Primary	*Revision*	*Total*
Knees	321 084	31 159	352 243
Hips	300 434	43 082	343 816
Total	621 518	74 241	696 059

Data from *Orthopaedic Network News.*[1]

FIGURE 2-1. Five-year retrieval of a failed Poly-2 tibial insert demonstrating a high component wear rate with infiltration of carbon fibers and polyethylene debris into surrounding tissue.

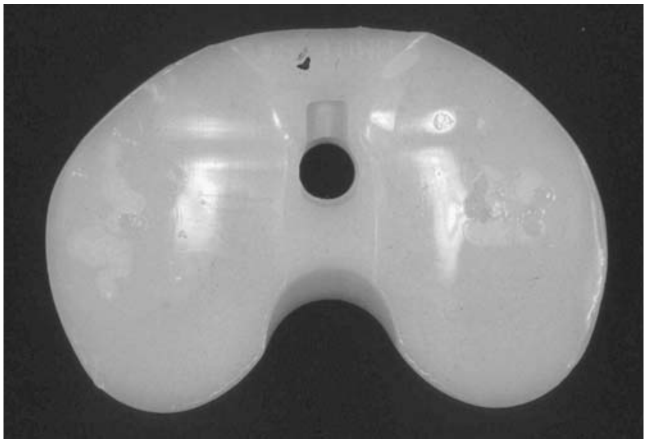


FIGURE 2-2. Three-year retrieval of a failed Hylamer-M tibial plateau demonstrating an unexpectedly high wear rate with corresponding wear and debris-induced inflammatory tissue response.

FIGURE 2-3. Six-year retrieval of a heat-pressed tibial component associated with polyethylene fatigue and early delamination.

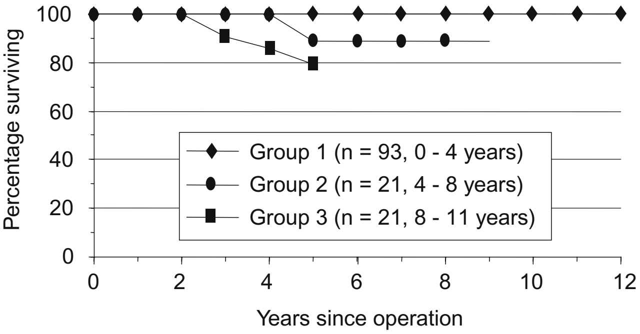


FIGURE 2-4. The influence of shelf storage on survival of a prosthetic knee plateau following gamma irradiation in air. (From Bohl, Bohl, Postak, et al.[34] by permission of *Clin Orthop*.)

FIGURE 2-5. A Group 2 plateau implanted after 7.6 years of shelf storage and retrieved 3.8 years after implantation. Gross delamination and pitting, characteristics of fatigue failure, are observed. (From Bohl, Bohl, Postak, et al.[34] by permission of *Clin Orthop*.)

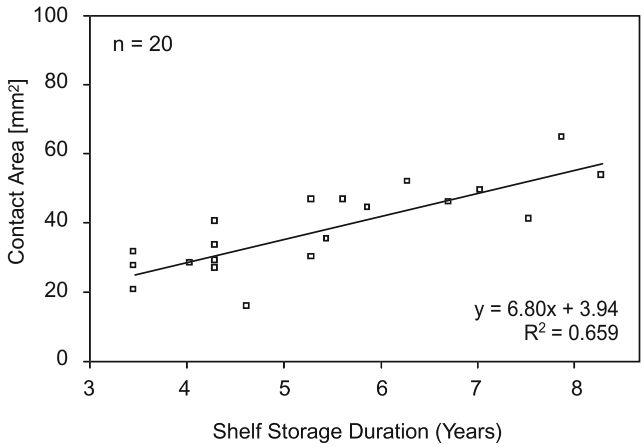
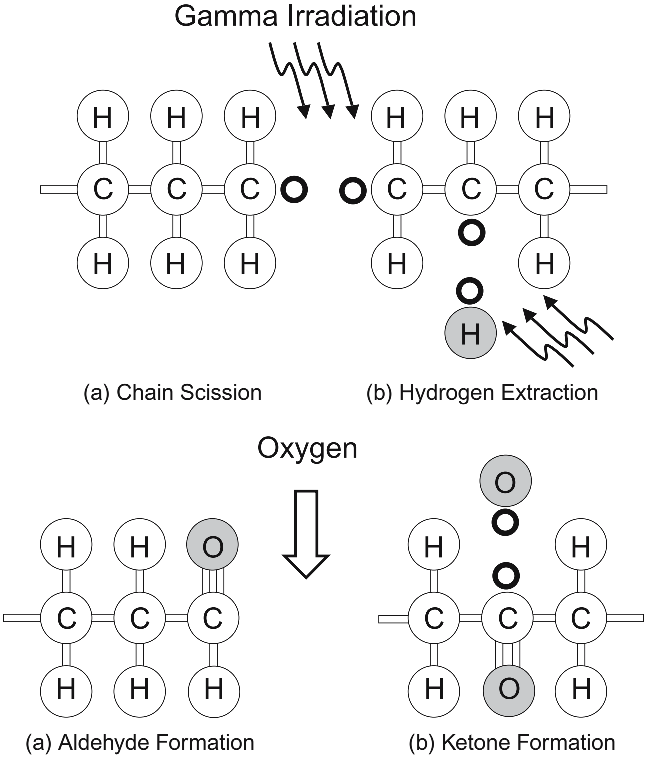


FIGURE 2-6. Tibial-femoral contact area for a 5.6-mm thick tibial plateau carrying >20 MPa stresses during articulation dramatically increases with lengthening shelf storage periods.

Further, laboratory studies indicate that as shelf storage increases, the amount of UHMWPE exposed to high surface stresses during articulation increases dramatically and is a contributing factor to early *in vivo* polymer failure[35–37] (Figure 2-6).

The explanation for these observations lies in the mechanics of the sterilization process, which facilitates breakage of polymer chains by the incoming gamma radiation, creating free radicals, which preferentially combine with available oxygen[38,39] (Figure 2-7). The onset of mass UHMWPE component production and device modularity resulted in extended component shelf storage before use. This was not a previous consideration, but ongoing shelf life oxidation offers an explanation for mechanical compromise of the polymer *in situ*[36,38,40,41] (Figure 2-8). It is also noted, in this regard, that *in vivo* component oxidation occurs, but to a lesser degree.[42]

FIGURE 2-7. Depicted polymer chain breakage following irradiation in air and combination with oxygen facilitating oxidative degradation of UHMWPE.



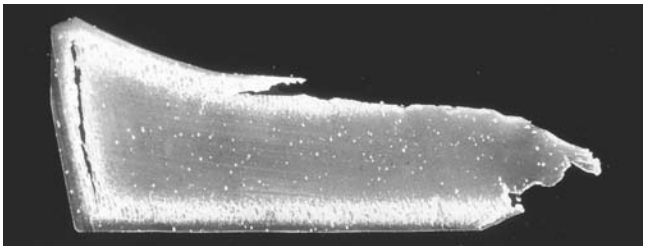


FIGURE 2-8. Three-year retrieval of a fully oxidized, gamma irradiated in air, UHMWPE tibial component demonstrating a circumferential white band indicative of polymer embrittlement after prolonged shelf life. Fusion defects from incomplete consolidation are noted.

Component Manufacturing Deficiencies

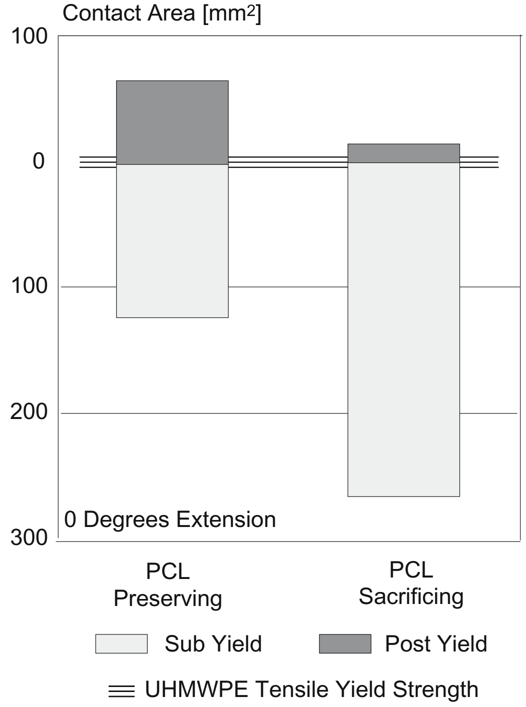
As knee designs have evolved, a growing appreciation of the avoidance of round-on-flat geometries through the ranges of knee flexion in favor of round-on-curved surfaces emerged.[32] The ability of a given design to minimize contact stresses during walking gait contributes to UHMWPE tibial component longevity. The increased tibial-femoral conformity realized in posterior cruciate ligament (PCL) sacrificing knee plateaus serves to enhance UHMWPE service life by attenuation of peak contact stresses responsible for material damage. This is appreciated in the comparison shown between PCL preserving and PCL sacrificing plateau geometries articulating against their respective, common femoral component (Figure 2-9).

The trend toward more conforming design geometries also has associated with it the expectation that femoral component tolerances be maintained during the manufacturing process. Failure to achieve this can dramatically decrease contact surfaces, elevate peak stresses, and, concurrent with articulation, is the harbinger of material damage[44] (Figure 2-10). This is of particular import with the current interest in mobile bearing knee designs, whose cited advantage is the maximization of contact surfaces during gait.[45]

Third-Body Wear

The interaction of third-body particulate between articulation surfaces in knee replacement consistently demonstrates catalysis of UHMWPE damage. Surface scratching of the metallic counterface resulting from these interactions further contributes to the wear process. Foreign

FIGURE 2-9. Contact areas by surface stress range of PCL-preserving and PCL-sacrificing tibial-femoral conformities at 0 degrees extension. The overall bar height depicts the total contact area. (From Heim, Postak, Greenwald[43] by permission of AAOS.)



body inclusions may derive from acrylic bone cement, entrapped bone, and beads from an incomplete sintering process or hydroxyapatite (HA) particulate (Figure 2-11).

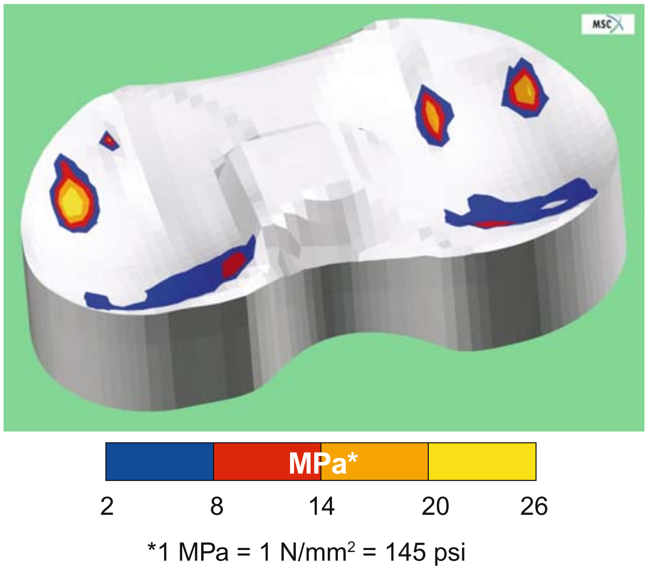


FIGURE 2-10. Finite element analysis of tibial-femoral contact areas and surface stresses of a contemporary mobile bearing knee design at 0 degrees extension. Poor mating of the articulating surfaces is observed resulting in peripheral contact with damaging stress levels.

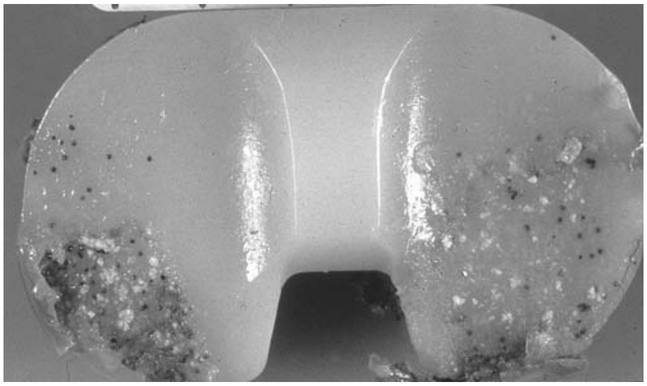


FIGURE 2-11. An early retrieval of a cementless, metal-backed tibial component demonstrating the effects of third-body entrapment. Bead embedment as well as delamination and pitting are observed in the posteromedial quadrant.

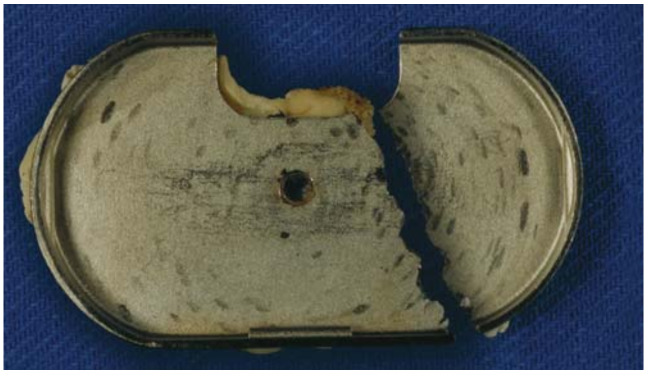
Component Design Influences

With the introduction of modularity, the interest in the all-poly tibia diminished, despite successful, long-term clinical reports.[46,47] Monoblock components were also introduced with the goal of optimizing stress transfer to the tibial bone surface.[48] Recently, attention has been drawn to the shortcomings of modular designs by the report of backside wear and an associated link to osteolysis and aseptic loosening.[49–58] Locking mechanism deficiency has been cited as a factor in allowing displacement between the insert and tibial tray to occur resulting in UHMWPE debris generation (Figure 2-12). Particulate transport to the intramedullary canal is facilitated through gaps at the locking mechanism interface as well as through screw holes when present.

Component Malalignment: A Surgical Prodrome

The forces and torques that occur during walking gait, particularly during toe-off, promote articulation in the posteromedial quadrant of tibial inserts.[59–63] Retrieved

FIGURE 2-12. Visualization of adhesive film transfer demonstrating UHMWPE insert rotatory micromotion in a modular tibial component.



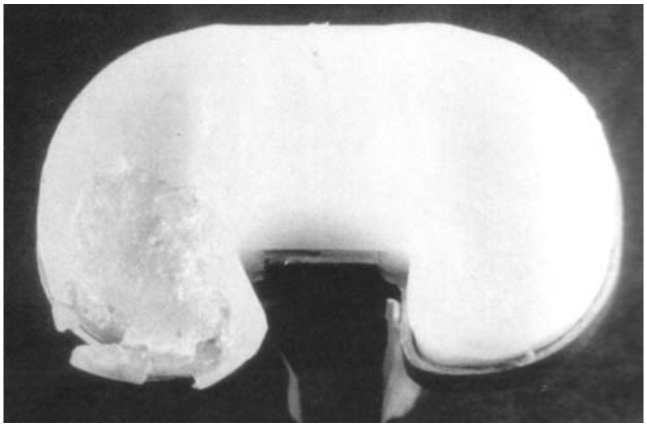


FIGURE 2-13. UHMWPE tibial component retrieval showing deformation and wear in the posteromedial portion of the insert. (From Swany, Scott,[68] by permission of *J Arthroplasty*.)

components of failed knee arthroplasties demonstrate UHMWPE damage patterns in this area[64–68] (Figure 2-13). Notwithstanding poor component design, causal factors include overloading the medial compartment, improper surgical correction or alignment of the bony structures, insufficient soft tissue balance and release, polyethylene cold flow near the edge of the tibial plateau, and surgical malrotation of the components.[64–68] In addition, the dynamic effects of lift-off and subsequent impact loading, and unusual patient kinematics further increase the potential for posteromedial failures.[69] The influence of surgical malrotation may be appreciated in Figure 2-14A, B, which demonstrate dramatic changes in location, contact area, and peak stresses for a PCL preserving knee in laboratory investigation.[70]

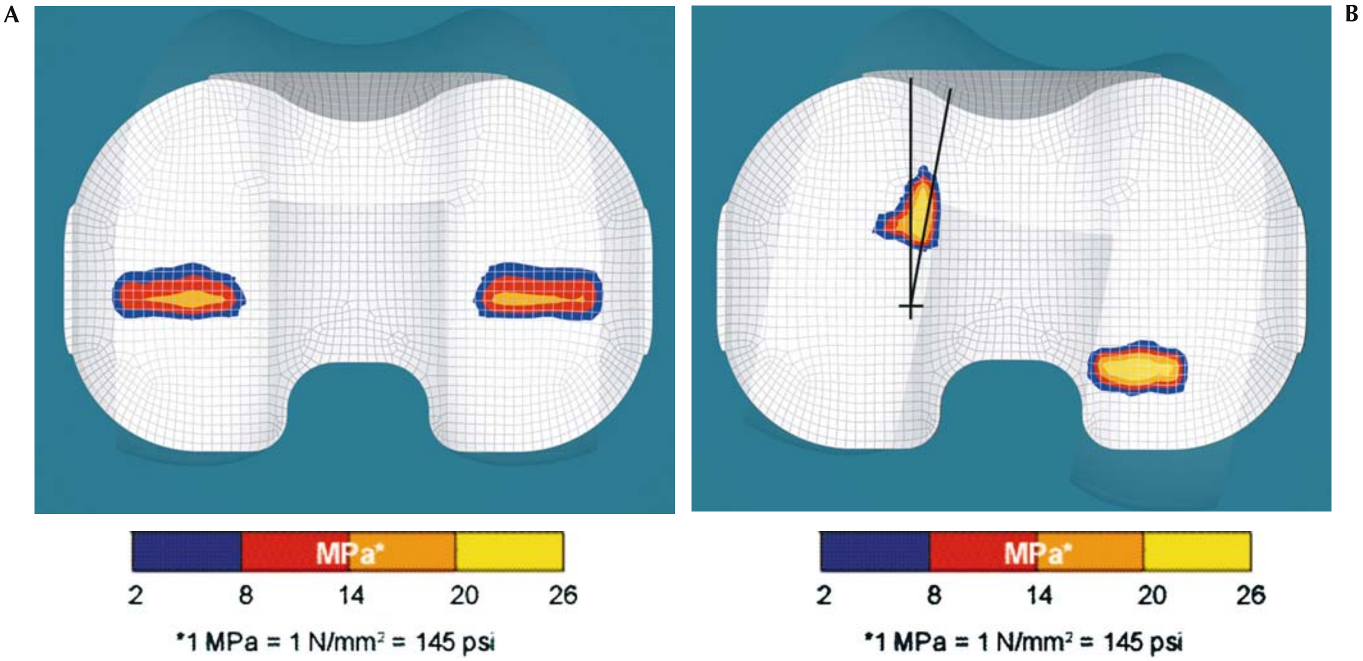
THE REMEDIES

UHMWPE Sterilization Techniques

Attempts to remove oxygen from the sterilization process include the use of inert gas and vacuum environments or by avoiding gamma irradiation altogether through the use of ethylene oxide (EtO) or gas plasmas.[71–73] Acetabular components sterilized by these techniques demonstrate a reduction in UHMWPE wear in hip simulation studies (Figure 2-15).

Today, orthopedic device manufacturers avoid the use of an air environment when packaging UHMWPE components sterilized through the gamma irradiation process. Further, sterilization dates are now standard on package labeling of UHMWPE components.

FIGURE 2-14. The distribution of contact stresses at the toe-off position of walking gait for a PCL preserving design at (A) neutral rotation and (B) after the application of a 16 N-m external torque, simulating deliberate component malalignment. A dramatic increase in peak contact stresses is observed, which is contributory to component damage. (From Morra, Postak, Plaxton, et al.[70] by permission of *Clin Orthop*.)



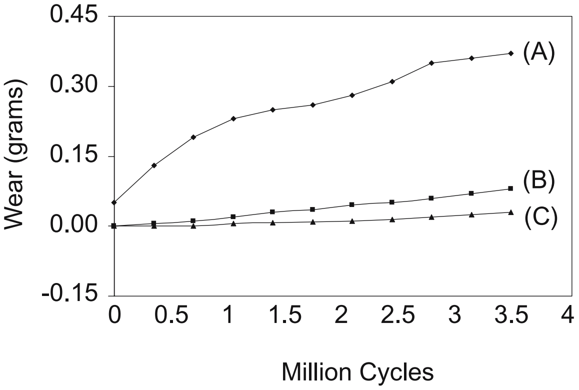


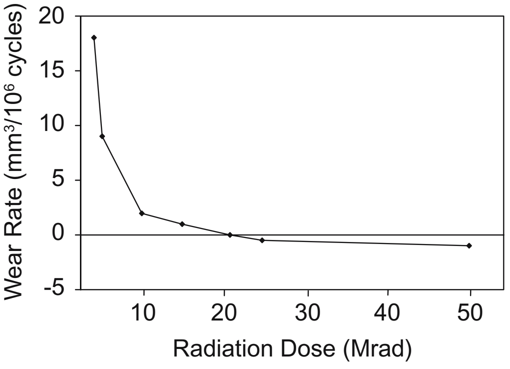
FIGURE 2-15. Hip simulator weight-loss comparison for aged (25 days at 78 degrees Celsius in O_2) compression-molded cup components: (A) gamma irradiated in air; (B) sterilized with ethylene oxide; and (C) gamma irradiated in a vacuum environment and use of barrier packaging. (From Greer, Schmidt, Hamilton,[72] by permission of *Trans Orthop Res Soc.*)

UHMWPE Processing Techniques

It is now quantitatively appreciated that increasing the gamma radiation dose above the 2.5 Mrad level used in conventional UHMWPE component sterilization, encourages free radicals to combine, creating crosslinks between the molecules of adjacent chains, which is further enhanced in an oxygen-free environment.[74–76] This graph from McKellop and coworkers is descriptive of this phenomenon in a simulator comparison of acetabular cup components (Figure 2-16). The volumetric wear per million cycles is dramatically reduced with increasing gamma radiation exposure.

There are clinical reports attributed to Oonishi and Grobbelaar, which describe *in vivo* UHMWPE wear reduction in acetabular components realized through increased crosslinking.[77–82] However, these studies employed large doses of gamma radiation (>50 Mrad), which are known to cause polymer embrittlement and yellowing. Wroblewski employing a chemically enhanced cross-linked polymer, achieved similar findings both *in vivo* and *in vitro*, when coupled with an Alumina articulation.[83]

FIGURE 2-16. Mean acetabular cup wear rates versus gamma dose level. (From McKellop, Shen, Lu, et al.[75] by permission of *J Orthop Res.*)



In some sense these isolated studies point the way to a new class of UHMWPEs, whose common denominator is an appreciation of the importance of increased crosslinking while minimizing oxidative degradation to reduce wear. Current methods used to manufacture these moderately to highly cross-linked UHMWPEs are shown (Figure 2-17). Process differences include (1) heating above or below the melt temperature of the polyethylene, (2) the type of radiation employed, (3) the radiation dose level, and (4) the endpoint sterilization.

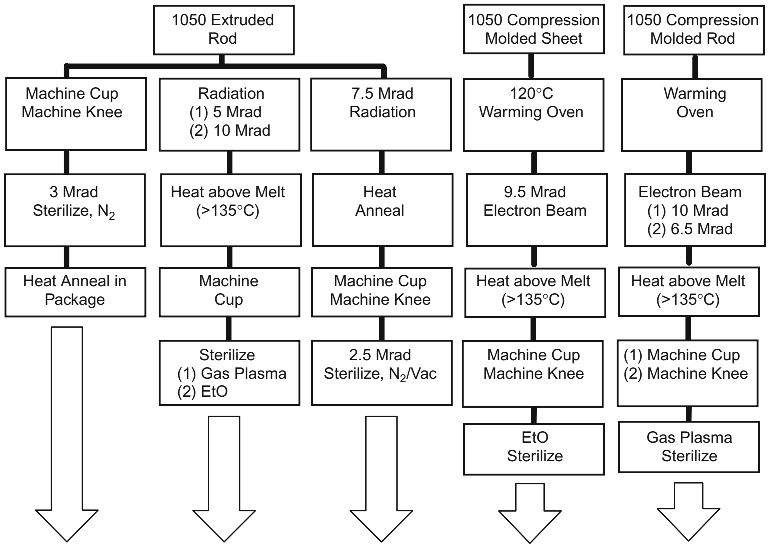
All have received Food and Drug Administration 510[k] clearance, allowing commercial distribution for both hip and knee components. Currently, there is a minimum of short-term clinical reports supporting the advantage of these increased cross-linked UHMWPEs for the hip[84–90] and knee.[91,92] However, impressive laboratory data have been produced, predominantly with regard to hip simulation.[93–97]

Manufacturing Optimization

The attainment of femoral component tolerances has markedly improved with the relatively recent use of computer-aided precision grinding as a standard finishing technique for metallic femoral knee components. This is particularly beneficial where small variations in surface contours have large effects on contact areas and surface stresses (Figure 2-18). The implications of this technique have potentially far-reaching consequences. As design specifications are produced with higher required tolerances, as in contemporary mobile bearing knee designs, the need for precision manufacturing is imperative (Figure 2-19).

Tibial Tray Design Improvement

Improving the capture mechanisms of UHMWPE tibial inserts is an ongoing design challenge. Minimizing insert microdisplacement over time will contribute to reduced UHMWPE debris generation. This notwithstanding, careful attention must also be paid to the tibial tray material and its surface finish. Just as polished, titanium femoral heads fell from clinical popularity as their surfaces easily scratched and wore during articulation,[98–100] modular tibial tray components should be manufactured using cobalt-chrome alloys. If, because of modular mismatch, microdisplacement is inevitable, the articulation surfaces should be optimized to reduce the potential for wear debris generation. From a design perspective, circumferential capture and the capping or avoidance of screw holes should be considered, so as to avoid potential



Process Name	**Heat Stabilized**	**CISM** (Cold Irradiated Subsequent Melt)	**CIAN** (Cold Irradiated Annealed Non-melt)	**WIAM** (Warm Irradiated Adiabatic Melting)	**WISM** (Warm Irradiated Subsequent Melt)
Product Name	*Duration™*	*(1) Marathon™* *(2) XLPE™*	*Crossfire™*	*Durasul®*	*(1) Longevity®* *(2) Prolong™*
Company	*Stryker Howmedica Osteonics*	*(1) DePuy / J&J* *(2) Smith + Nephew*	*Stryker Howmedica Osteonics*	*Centerpulse Orthopedics / Zimmer*	*Zimmer*

FIGURE 2-17. Current methods used to manufacture moderately to highly cross-linked UHWMPE.

FIGURE 2-18. A comparison of tibial-femoral contact areas by surface stress range for belt finishing and computer-aided precision grinding techniques of a single femoral component design at 0 degrees extension. The overall bar height depicts the total contact area. (From Helm, Postak, Greenwald[43] by permission of AAOS.)

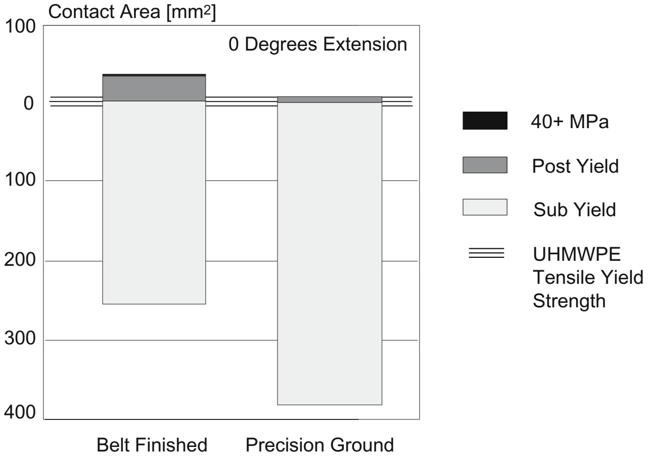
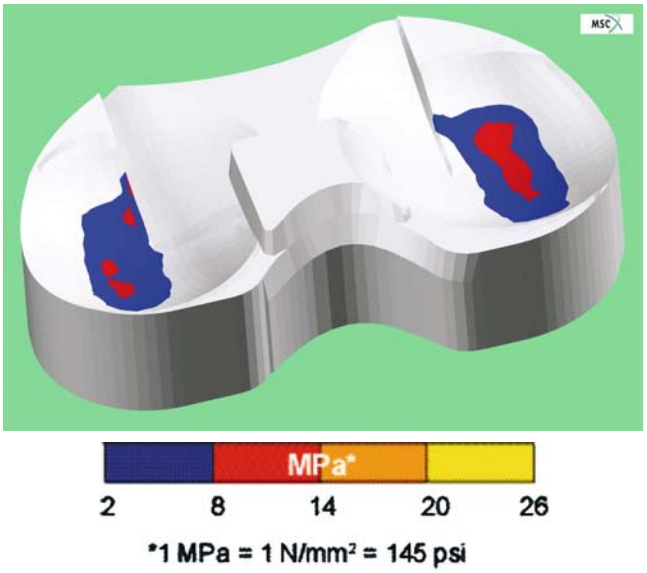


FIGURE 2-19. Finite element analysis demonstrating the optimization of tibial-femoral contact areas and surface stresses resulting from quality controlled finishing of the component demonstrated earlier in Figure 2-10. It is apparent that use of the conforming geometries has been achieved with the resulting diminishment of peak contact stresses.



pathways for debris transport.[101–105] A further consequence of modularity is the employment of highly cross-linked UHMWPE inserts whose fracture toughness is reduced. Locking points in tray design represent foci for stress concentrators, increasing the potential for crack initiation, the propagation of which occurs more rapidly in these materials than conventional polyethylene.[106]

Surgical Optimization

The increasing emphasis on templating and the relatively recent introduction of computer-assisted navigation techniques offer the promise that component malalignment may ultimately be minimized.[107–109] Eliminating the outliers in component placement will contribute to diminishing UHMWPE material damage in knee arthroplasty. Continued improvements in instrument design go hand-in-hand with the achievement of this goal.

Patient Factors: Do They Really Matter?

Overenthusiastic patient use following total knee arthroplasty has been cited as a factor influencing failure.[110–112] Its occurrence, however, has generally been described in singular case reports in much the same way as failure attributed to obesity. Series reports do not support a relationship between increased body mass index and device failure following arthroplasty.[113–118] Surgical preference, however, weighs in favor of the lightweight patient as the ideal arthroplasty candidate.[119] However, it is known from both physical laboratory testing and finite element analysis that load magnitude in combination with displacement are factors influencing UHMWPE damage.[120–127] While a recommendation for patient weight loss before surgery may be justified from these laboratory investigations, the clinical reality of achieving this does not lie in the patient's or surgeon's favor.[128]

THE CONCERNS

Highly Cross-Linked UHMWPE Use in TKA

The proclaimed advantage of highly cross-linked UHMWPEs lies in the reduction of wear debris generation through enhanced crosslinking of the polymer chains coincident with the elimination of oxidation. However, changes in the mechanical properties of these materials, particularly in their reduced resistance to fatigue crack propagation (fracture toughness) raises concerns about their long-term suitability in hip and knee components where locking mechanisms offer foci for stress risers[106] (Figures 2-20, 2-21, and 2-22). An appreciation of the differing modes of hip (abrasion and adhesion) and knee (pitting and delamination) failure, confirmed through conventional UHMWPE component retrieval,[132–134] suggests that a universal, highly cross-linked polymer may not be appropriate.

Investigation into the means by which fracture toughness and ultimate tensile strength of these new polymers may be increased is and should be an ongoing quest, particularly if their rapid employment will lead to obsolescence of conventional UHMWPE. Its furthest hope in knee replacement application would be a reduction in the capacity for these materials to pit and delaminate or, in other words, when the knee behaves like a hip in terms of its wear process. This reality may be appreciated with designs of increasing conformity such as those found in mobile bearing knees.

FIGURE 2-20. A 1-year conventional UHMWPE, primary acetabular liner demonstrating crack initiation and propagation. Failure initiated at a sharp edge of a locking point. (From Tradonsky, Postak, Froimson[129] by permission of *Clin Orthop*.)

FIGURE 2-21. A 10-month highly cross-linked UHMWPE, revision acetabular liner demonstrating crack initiation and propagation. The decision to retain the acetabular shell in an almost vertical and anteverted position contributed to this early failure, which was compounded by the decision to use a 40-mm femoral head and a correspondingly thin liner. (From Halley, Glassman, Crowninshield[130] by permission of *J Bone Joint Surg*.)

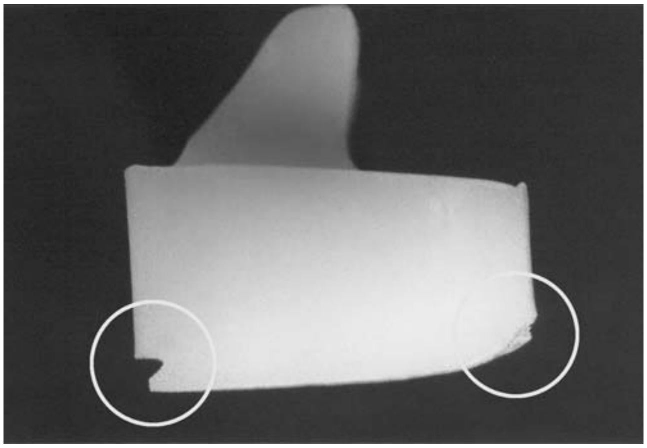


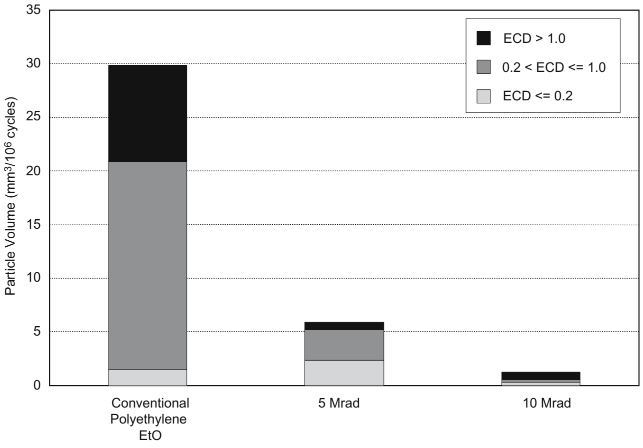
FIGURE 2-22. A 3-year failure of a constrained condylar conventional UHMWPE tibial insert. Failure of the posterior locking mechanism resulted in posterior component lift-off. (From Ries[131] by permission of *J Bone Joint Surg.*)

Particle Bioreactivity

Conventional wisdom and our experience particular to hip arthroplasty suggest that osteolytic response is associated with both particle size and debris volume. Laboratory hip simulator experiments have shown that UHMWPE particle volumes in various size ranges are dependent on radiation dose[135] (Figures 2-23 and 2-24). The greatest potential for cytokine release, the first step in the sequelae leading to osteolysis, following macrophage debris encapsulation is at the <1 micron level. Ingram et al. have suggested that highly cross-linked UHMWPE debris obtained from scratched surface articulation is bioreactive when placed in culture medium and appears to be volume dependent.[136]

The influence of surface roughness has been further investigated by Scott et al. in a hip simulator comparison

FIGURE 2-23. Comparative volumes of acetabular particle generation for different size ranges per million cycles for conventional and highly cross-linked UHMWPEs at 5 and 10 Mrads resulting from hip simulation. ECD, equivalent circular diameter. (From Ries, Scott, Jani,[135] by permission of *J Bone Joint Surg.*)



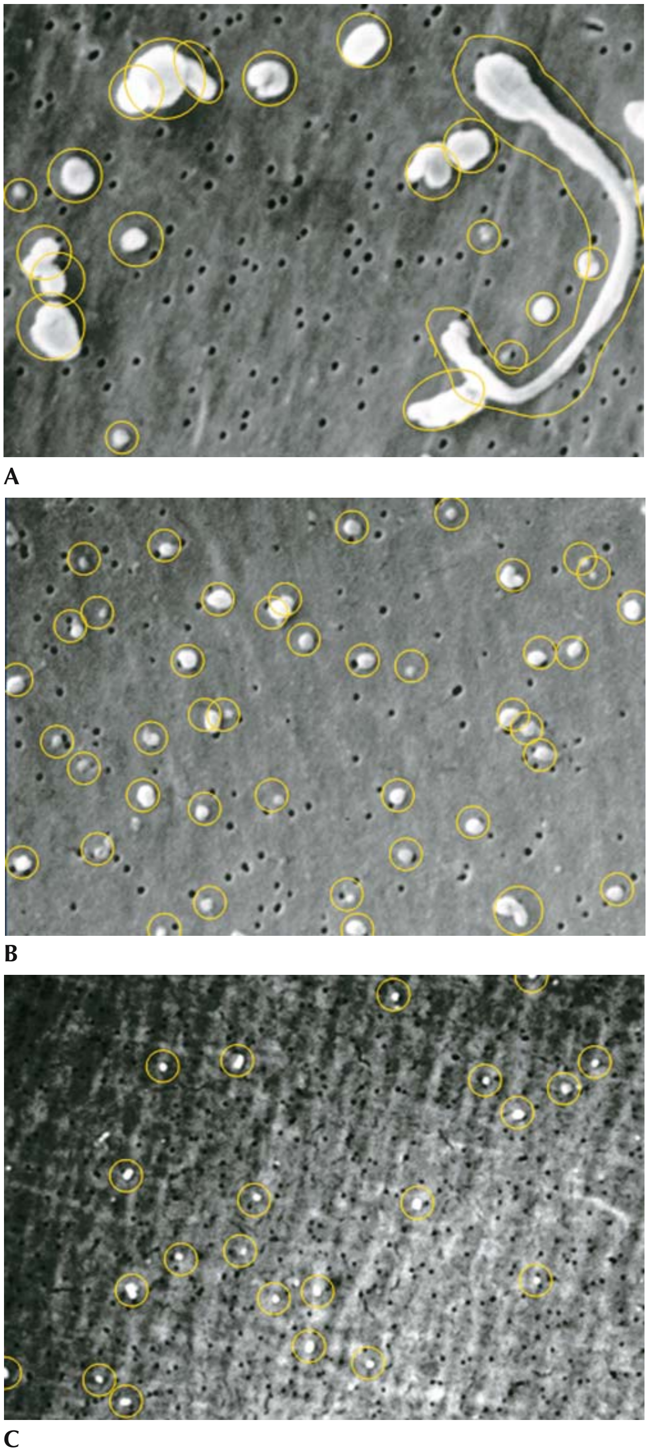


FIGURE 2-24. Corresponding SEM visualization (10000×) of particle distribution for (A) conventional and (B and C) highly cross-linked UHMWPEs at 5 and 10 Mrads, respectively, employing a 0.05-micron filter. The particles are highlighted for appreciation. (From Ries, Scott, Jani,[135] by permission of *J Bone Joint Surg.*)

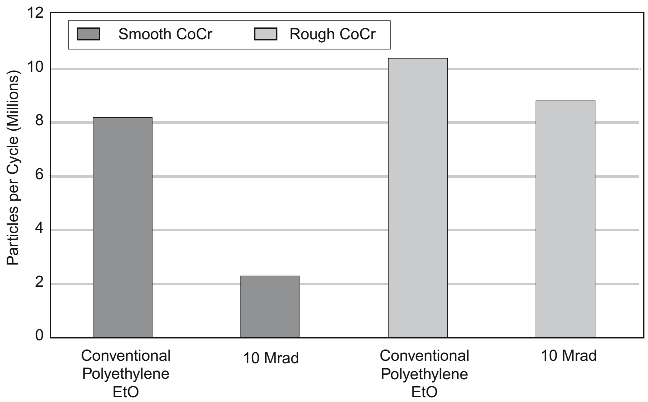


FIGURE 2-25. The influence of smooth and roughened femoral head surfaces on particle generation for conventional and highly cross-linked UHMWPE acetabular components resulting from hip simulation. (From Good, Ries, Barrack, et al.[139] by permission of *J Bone Joint Surg Am.*)

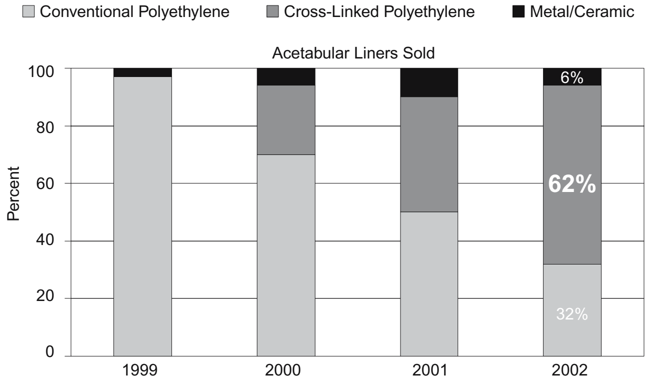
between conventional, EtO, and 10 Mrad polyethylene components.[137] As one appreciates from Figure 2-25, roughened surfaces have a negative influence on particle production where highly cross-linked polyethylenes are employed. This has been challenged most recently by Muratoglu et al. in a study in which retrieved femoral components were articulated in knee simulation against a highly cross-linked polyethylene.[138]

Alternatives to reduce the influence of surface roughness on femoral component design have recently been reported using fully oxidized zirconium surfaces. This has relevance on the long-term viability of knee articulations with conventional UHMWPE tibial inserts, but its performance is unknown with highly cross-linked materials.[139,140]

Direct-to-Consumer Marketing

Further, it is no small coincidence that almost 62% of all polyethylene acetabular components sold in the United States today are constituted of highly cross-linked polyethylenes in their various formulations[1] (Figure 2-26). Cost as well as patient selection and the unknown clinical realities of long-term series reporting are concerns with these materials that only *in vivo* time will elucidate. The march of progress toward increasing use of these materials—in the relative absence of mid- and long-term clinical reports—portrays a rapid direct-to-consumer marketing philosophy employed by orthopedic manufacturers for both the orthopedic surgeon and the patients they serve.

FIGURE 2-26. Histogram illustrating the growth of highly cross-linked UHMWPE acetabular component sales in the United States. (Data from *Orthopaedic Network News.*[1])



THE PROMISE

The previous remarks have attempted to define problems, solutions, and unknown performance factors of both conventional and emerging highly cross-linked UHMWPE materials currently used in knee arthroplasty. What is important for the reader to appreciate is that the description of employment of highly cross-linked polymers in knee arthroplasty is an evolving experience, which will find advocacy or limitation in what is now a tandem laboratory and clinical approach. The passage of *in vivo* time, as has always been, will be the defining factor in their use.

REFERENCES

1. *Orthopaedic Network News.* 14:3, Ann Arbor, MI: Mendenhall Associates, Inc.; 2003.
2. Aglietti P, Buzzi R, De Felice R, et al. The Insall-Burstein total knee replacement in osteoarthritis: a 10-year minimum follow-up. *J Arthroplasty.* 1999;14(5):560–565.
3. Berger RA, Rosenberg AG, Barden RM, et al. Long-term followup of the Miller-Galante total knee replacement. *Clin Orthop.* 2001;388:58–67.
4. Buechel FF. Long-term followup after mobile-bearing total knee replacement. *Clin Orthop.* 2002;404:40–50.
5. Ewald FC, Wright RJ, Poss R, et al. Kinematic total knee arthroplasty: a 10- to 14-year prospective follow-up review. *J Arthroplasty.* 1999;14(4):473–480.
6. Gill GS, Joshi AB. Long-term results of cemented, posterior cruciate ligament-retaining total knee arthroplasty in osteoarthritis. *Am J Knee Surg.* 2001;14(4):209–214.
7. Gill GS, Joshi AB, Mills DM. Total condylar knee arthroplasty. 16- to 21-year results. *Clin Orthop.* 1999;367:210–215.
8. Keating EM, Meding JB, Faris PM, et al. Long-term followup of nonmodular total knee replacements. *Clin Orthop.* 2002;404:34–39.

9. Kelly MA, Clarke HD. Long-term results of posterior cruciate-substituting total knee arthroplasty. *Clin Orthop.* 2002;404:51–57.
10. Pavone V, Boettner F, Fickert S, et al. Total condylar knee arthroplasty: a long-term followup. *Clin Orthop.* 2001;388: 18–25.
11. Rodriguez JA, Bhende H, Ranawat CS. Total condylar knee replacement: a 20-year followup study. *Clin Orthop.* 2001; 388:10–17.
12. Whiteside LA. Long-term followup of the bone-ingrowth Ortholoc knee system without a metal-backed patella. *Clin Orthop.* 2001;388:77–84.
13. Brander VA, Malhotra S, Jet J, et al. Outcome of hip and knee arthroplasty in persons aged 80 years and older. *Clin Orthop.* 1997;345:67–78.
14. Diduch DR, Insall JN, Scott WN, et al. Total knee replacement in young, active patients. *J Bone Joint Surg Am.* 1997; 79(4):575–582.
15. Duffy GP, Trousdale RT, Stuart MJ. Total knee arthroplasty in patients 55 years old or younger. 10- to 17-year results. *Clin Orthop.* 1998;356:22–27.
16. Gill GS, Joshi AB. Total knee arthroplasty in the young. *J Arthroplasty.* 2004;19(2):255.
17. Hilton AI, Back DL, Espag MP, et al. The octogenarian total knee arthroplasty. *Orthopedics.* 2004;27(1):37–39.
18. Hofmann AA, Heithoff SM, Camargo M. Cementless total knee arthroplasty in patients 50 years or younger. *Clin Orthop.* 2002;404:102–107.
19. Joshi AB, Markovic L, Gill GS. Knee arthroplasty in octogenarians: results at 10 years. *J Arthroplasty.* 2003; 18(3):295–298.
20. Laskin RS. Total knee replacement in patients older than 85 years. *Clin Orthop.* 1999;367:43–49.
21. Pagnano MW, Levy BA, Berry DJ. Cemented all polyethylene tibial components in patients age 75 years and older. *Clin Orthop.* 1999;367:73–80.
22. Tankersley WS, Hungerford DS. Total knee arthroplasty in the very aged. *Clin Orthop.* 1995;316:45–49.
23. 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(7):1080–1090.
24. Tanner MG, Whiteside LA, White SE. Effect of polyethylene quality on wear in total knee arthroplasty. *Clin Orthop.* 1995;317:83–88.
25. Won CH, Rohatgi, Kraay MJ, et al. Effect of resin type and manufacturing method on wear of polyethylene tibial components. *Clin Orthop.* 2000;376:161–171.
26. Wrona M, Mayor MB, Collier JP, et al. The correlation between fusion defects and damage in tibial polyethylene bearings. *Clin Orthop.* 1994;299:92–103.
27. Sclippa E, Piekarski K. Carbon fiber reinforced polyethylene for possible orthopedic uses. *J Biomed Mater Res.* 1973;7:59–70.
28. Champion AR, Li S, Saum K, et al. The effect of crystallinity on the physical properties of UHMWPE. *Trans Orthop Res Soc.* 1994;19:585.
29. Busanelli L, Squarzoni S, Brizio L, et al. Wear in carbon fiber-reinforced polyethylene (poly-two) knee prostheses. *Chir Organi Mov.* 1996;81(3):263–267.
30. Collier JP, Bargmann LS, Currier BH, et al. An analysis of hylamer and polyethylene bearings from retrieved acetabular components. *Orthopedics.* 1998;21(8):865–871.
31. Wright TM, Rimnac CM, Stulberg SD, et al. Wear of polyethylene in total joint replacements. Observations from retrieved PCA knee implants. *Clin Orthop.* 1992;276: 126–134.
32. Collier JP, Mayor MB, McNamara JL, et al. Analysis of the failure of 122 polyethylene inserts from uncemented tibial knee components. *Clin Orthop.* 1991;273:232–242.
33. Peters PC, Engh GA, Dwyer KA, et al. Osteolysis after total knee arthroplasty without cement. *J Bone Joint Surg Am.* 1992;74:864–876.
34. Bohl JR, Bohl WR, Postak PD, et al. The effects of shelf life on clinical outcome for gamma sterilized polyethylene tibial components. *Clin Orthop.* 1999;267:28–38.
35. Collier JP, Sperling DK, Currier JH, et al. Impact of gamma sterilization on clinical performance of polyethylene in the knee. *J Arthroplasty.* 1996;11:377–389.
36. Currier BH, Currier JH, Collier JP, et al. Shelf life and in vivo duration: impacts on performance of tibial bearings. *Clin Orthop.* 1997;342:111–122.
37. Heim CS, Postak PD, Greenwald AS. The influence of shelf storage duration on gamma irradiated UHMWPE tibial components. *Orthop Trans.* 1998–9;22:149–150.
38. Collier JP, Sutula LC, Currier BH, et al. Overview of polyethylene as a bearing material: Comparison of sterilization methods. *Clin Orthop.* 1996;333:76–86.
39. Nusbaum HJ, Rose RM. The effects of radiation sterilization on the properties of ultrahigh molecular weight polyethylene. *J Biomed Mater Res.* 1979;13:557–576.
40. Ries MD, Weaver K, Rose RM, et al. Fatigue strength of polyethylene after sterilization by gamma irradiation or ethylene oxide. *Clin Orthop.* 1996;333:87–95.
41. Rimnac CM, Klein RW, Betts F, et al. Post-irradiation ageing of ultra-high molecular weight polyethylene. *J Bone Joint Surg Am.* 1994;76:1052–1056.
42. Leibovitz BE, Siegel BV: Aspects of free radical reactions in biological systems: aging. *J Gerontol.* 1980;35: 45–56.
43. Helm CS, Postak PD, Greenwald AS. Factors Influencing the longevity of UHMWPE tibial components. In: Pritchard D, ed. *Instructional Course Lectures*, Vol. 45. Chicago, IL; American Academy of Orthopaedic Surgeons, 1996.
44. Morra EA, Postak PD, Greenwald AS. The influence of mobile bearing knee geometry on the wear of UHMWPE tibial inserts: a finite element study. *Orthop Trans.* 1998–9; 22(1):148.

45. Buechel FF, Pappas MJ. The New Jersey low-contact-stress knee replacement system: a biomechanical rationale and review of the first 123 cemented cases. *Arch Orthop Trauma Surg.* 1986;105(4):197–204.
46. Brassard MF, Insall JN, Scuderi GR, et al. Does modularity affect clinical success? a comparison with a minimum 10-year follow-up. *Clin Orthop.* 2001;388:26–32.
47. Rodriguez JA, Baez N, Rasquinha V, et al. Metal-backed and all-polyethylene tibial components in total knee replacement. *Clin Orthop.* 2001;392:174–183.
48. Ritter MA, Worland R, Saliski J, et al. Flat-on-flat, nonconstrained, compression molded polyethylene total knee replacement. *Clin Orthop.* 1995;321:79–85.
49. Chapman-Sheath P, Cain S, Bruce WJ, et al. Surface roughness of the proximal and distal bearing surface of mobile bearing total knee prostheses. *J Arthroplasty.* 2002;17(6): 713–717.
50. Conditt MA, Stein JA, Noble PC. Factors affecting the severity of backside wear of modular tibial inserts. *J Bone Joint Surg Am.* 2004;86(2):305–311.
51. Cuckler JM, Lemons J, Tamarapalli JR, et al. Polyethylene damage on the nonarticular surface of modular total knee prostheses. *Clin Orthop.* 2003;410:248–253.
52. Engh GA, Lounici S, Rao AR, et al. In vivo deterioration of tibial baseplate locking mechanisms in contemporary modular total knee components. *J Bone Joint Surg Am.* 2001;83(11):1660–1665.
53. Li S, Scuderi G, Furman BD, et al. Assessment of backside wear from the analysis of 55 retrieved tibial inserts. *Clin Orthop.* 2002;404:75–82.
54. Parks NL, Engh GA, Topoleski T, et al. Modular tibial insert micromotion: a concern with contemporary knee implants. *Clin Orthop.* 1998;356:10–15.
55. Rao AR, Engh GA, Collier MB, et al. Tibial interface wear in retrieved total knee components and correlations with modular insert motion. *J Bone Joint Surg Am.* 2002; 84(10): 1849–1855.
56. Surace MF, Berzins A, Urban RM, et al. Backsurface wear and deformation in polyethylene tibial inserts retrieved postmortem. *Clin Orthop.* 2002;404:14–23.
57. Wasielewski RC, Parks N, Williams I, et al. Tibial insert undersurface as a contributing source of polyethylene wear debris. *Clin Orthop.* 1997;345:53–59.
58. Wasielewski RC. The causes of insert backside wear in total knee arthroplasty. *Clin Orthop.* 2002;404:232–246.
59. Apkarian J, Naumann S, Cairns B. A three-dimensional kinematic and dynamic model of the lower limb. *J Biomech.* 1989;22:143–155.
60. LaFortune MA, Cavanaugh PR, Sommer HJ, et al. Three-dimensional kinematics of the human knee during walking. *J Biomech.* 1992;25:347–357.
61. Morrison JB. Function of the knee joint in various activities. *Biomed Eng.* 1969;4:573–580.
62. Murray MP, Drought AB, Kory RC. Walking patterns in normal men. *J Bone Joint Surg Am.* 1964;46:335–360.
63. Paul JP. Forces transmitted by joints in the human body. *Proc Inst Mech Eng.* 1967;181:358.
64. Cameron HU. Tibial component wear in total knee replacement. *Clin Orthop.* 1994;309:29–32.
65. Eckhoff DG, Metzger RG, Vedewalle MV. Malrotation associated with implant alignment technique in total knee arthroplasty. *Clin Orthop.* 1995;321:28–31.
66. Fehring TK. Rotational malalignment of the femoral component in total knee arthroplasty. *Clin Orthop.* 2000;380: 72–79.
67. Lewis P, Rorabeck CH, Bourne RB, et al. Posteromedial tibial polyethylene failure in total knee replacements. *Clin Orthop.* 1994;299:11–17.
68. Swany MR, Scott RD. Posterior polyethylene wear in posterior cruciate ligament-retaining total knee arthroplasty: a case study. *J Arthroplasty.* 1993;8:439–846.
69. Dennis DA, Komistek RD, Cheal EJ, et al. In vivo femoral condylar lift-off in total knee arthroplasty. *Orthop Trans.* 1997;21:1112.
70. Morra EA, Postak PD, Plaxton NA, et al. The effects of external torque on polyethylene tibial insert damage patterns. *Clin Orthop.* 2003;410:90–100.
71. Fisher J, Reeves EA, Isaac GH, et al. Comparison of aged and non-aged ultrahigh molecular weight polyethylene sterilized by gamma irradiation and by gas plasma. *J Mater Sci Mater Med.* 1997;8:375–378.
72. Greer KW, Schmidt MB, Hamilton JV. The hip simulator wear of gamma-vacuum, gamma-air, and ethylene oxide sterilized UHMWPE following a severe oxidative challenge. *Trans Orthop Res Soc.* 1998;23:52.
73. McGloughlin TM, Kavanagh AG. Wear of ultra-high molecular weight polyethylene (UHMWPE) in total knee prostheses: a review of key influences. *Proc Inst Mech Eng.* 2000;214:349–359.
74. Kurtz SM, Muratoglu OK, Evans M, et al. Advances in the processing, sterilization, and crosslinking of ultra-high molecular weight polyethylene for total joint arthroplasty. *Biomaterials.* 1999;20(18):1659–1688.
75. McKellop H, Shen FW, Lu B, et al. Development of an extremely wear-resistant ultra high molecular weight polyethylene for total hip replacements. *J Orthop Res.* 1999;17(2):157–167.
76. Muratoglu OK, Bragdon CR, O'Connor DO, et al. A novel method of cross-linking ultra-high-molecular-weight polyethylene to improve wear, reduce oxidation, and retain mechanical properties. *J Arthroplasty.* 2001; 16(2):149–160.
77. Oonishi H, Kadoya Y, Masuda S. Gamma-irradiated cross-linked polyethylene in total hip replacements—analysis of retrieved sockets after long-term implantation. *J Biomed Mater Res.* 2001;58(2):167–171.

78. Oonishi H, Kadoya Y. Wear of high-dose gamma-irradiated polyethylene in total hip replacements. *J Orthop Sci.* 2000;5(3):223–228.
79. Oonishi H, Clarke IC, Masuda S, et al. Study of retrieved acetabular sockets made from high-dose, cross-linked polyethylene. *J Arthroplasty.* 2001;16(8)(Suppl): 129–133.
80. Oonishi H, Clarke IC, Yamamoto K, et al. Assessment of wear in extensively irradiated UHMWPE cups in simulator studies. *J Biomed Mater Res.* 2004;68(1):52–60.
81. Grobbelaar CJ, de Plessis TA, Marais F. The radiation improvement of polyethylene prostheses. a preliminary study. *J Bone Joint Surg Br.* 1978;60(3):370–374.
82. Yamamoto K, Masaoka T, Manaka M, et al. Micro-wear features on unique 100-Mrad cups: two retrieved cups compared to hip simulator wear study. *Acta Orthop Scand.* 2004;75(2):134–141.
83. Wroblewski BM, Siney PD, Dowson D, et al. 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(2):280–285.
84. Bradford L, Baker DA, Graham J, et al. Wear and surface cracking in early retrieved highly cross-linked polyethylene acetabular liners. *J Bone Joint Surg Am.* 2004;86(6): 1271–1282.
85. Bradford L, Kurland R, Sankaran M, et al. Early fallure due to osteolysis associated with contemporary highly cross-linked ultra-high molecular weight polyethylene. A case report. *J Bone Joint Surg Am.* 2004;86(5):1051–1056.
86. Heisel C, Silva M, dela Rosa MA, et al. Short-term in vivo wear of cross-linked polyethylene. *J Bone Joint Surg Am.* 2004;86(4):748–751.
87. Hopper RH Jr, Young AM, Orishimo KF, et al. 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(7 Suppl 1):60–67.
88. Sychterz CJ, Orishimo KF, Engh CA. Sterilization and polyethylene wear: clinical studies to support laboratory data. *J Bone Joint Surg Am.* 2004;86(5):1017–1022.
89. Muratoglu OK, Greenbaum ES, Bragdon CR, et al. Surface analysis of early retrieved acetabular polyethylene liners. A comparison of conventional and highly crosslinked polyethylenes. *J Arthroplasty.* 2004;19(1):68–77.
90. Digas G, Karrholm J, Thanner J, et al. Highly cross-linked polyethylene in cemented THA: randomized study of 61 hips. *Clin Orthop.* 2003;417:126–138.
91. Fisher J, McEwen HM, Barnett PI, et al. Influences of sterilizing techniques on polyethylene wear. *Knee.* 2004; 11(3):173–176.
92. Muratoglu OK, Ruberti J, Melotti S, et al. Optical analysis of surface changes on early retrieval of highly cross-linked and conventional polyethylene tibial inserts. *J Arthroplasty.* 2003;18(7)(Suppl):42–47.
93. Bragdon CR, Jasty M, Muratoglu OK, et al. Third-body wear of highly cross-linked polyethylene in a hip simulator. *J Arthroplasty.* 2003;18(5):553–561.
94. McEwen HMJ, Farrar R, Auger DD, et al. Reduction of wear in fixed bearing total knee replacement using crosslinked UHMWPE. *Trans Orthop Res Soc.* 2003;28(2): 1428.
95. Kurtz SM, Pruitt LA, Jewett CW, et al. Radiation and chemical crosslinking promote strain hardening behavior and molecular alignment in ultra high molecular weight polyethylene during multi-axial loading conditions. *Biomaterials.* 1999;20(16):1449–1462.
96. Muratoglu OK, Bragdon CR, O'Connor DO, et al. Aggressive wear testing of a cross-linked polyethylene in total knee arthroplasty. *Clin Orthop.* 2002;404:89–95.
97. Muratoglu OK, Merrill EW, Bragdon CR, et al. Effects of radiation, heat and aging on in vitro wear resistance of polyethylene. *Clin Orthop.* 2003;417:253–262.
98. Bankston AB, Faris PM, Keating EM, et al. Polyethylene wear in total hip arthroplasty in patient-matched groups. A comparison of stainless steel, cobalt chrome, and titanium-bearing surfaces. *J Arthroplasty.* 1993;8(3):315–322.
99. Lombardi AV Jr, Mallory TH, Vaughn BK, et al. Aseptic loosening in total hip arthroplasty secondary to osteolysis induced by wear debris from titanium-alloy modular femoral heads. *J Bone Joint Surg Am.* 1989;71(9): 1337–1342.
100. McGovern TE, Black J, Jacobs JJ, et al. In vivo wear of Ti6Al4V femoral heads: a retrieval study. *J Biomed Mater Res.* 1996;32(3):447–457.
101. Berger RA, Lyon JH, Jacobs JJ, et al. Problems with cementless total knee arthroplasty at 11 years followup. *Clin Orthop.* 2001;392:196–207.
102. Engh GA, Parks NL, Ammeen DJ. Tibial osteolysis in cementless total knee arthroplasty. A review of 25 cases treated with and without tibial component revision. *Clin Orthop.* 1994;309:33–43.
103. Ezzet KA, Garcia R, Barrack RL. Effect of component fixation method on osteolysis in total knee arthroplasty. *Clin Orthop.* 1995;321:86–91.
104. Lewis PL, Rorabeck CH, Bourne, RB. Screw osteolysis after cementless total knee replacement. *Clin Orthop.* 1995;321: 173–177.
105. Peters PC Jr, Engh GA, Dwyer KA, et al. Osteolysis after total knee arthroplasty without cement. *J Bone Joint Surg Am.* 1992;74(6):864–876.
106. 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(4):573–581.
107. Jenny JY, Boeri C. Computer-assisted implantation of total knee prostheses: a case control comparative study with

classical instrumentation. *Comput Aided Surg.* 2001;6(4): 217–220.

108. Krackow KA, Phillips MJ, Bayers-Thering M, et al. Computer-assisted total knee arthroplasty: navigation in TKA. Orthopedics 2003;26(10):1017–1023.
109. Stulberg SD. how accurate is current TKR instrumentation? *Clin Orthop.* 2003;416:177–184.
110. Lavernia CJ, Sierra RJ, Hungerford DS, et al. Activity level and wear in total knee arthroplasty. *J Arthroplasty.* 2001; 16(4):446–453.
111. Mont MA, Rajadhyaksha AS, Marxen JL, et al. Tennis after total knee arthroplasty. *Am J Sports Med.* 2002;30(2): 163–166.
112. Seedhom BB, Wallbridge NC. Walking activities and wear of prostheses. *Ann Rheum Dis.* 1985;44:838.
113. Benjamin J, Tucker T, Ballesteros P. Is obesity a contraindication to bilateral total knee arthroplasties under one anesthetic? *Clin Orthop.* 2001;392:190–195.
114. Deshmukh RG, Hayes JH, Pinder IM. Does body weight influence outcome after total knee arthroplasty? a 1-year analysis. *J Arthroplasty.* 2002;17(3):315–319.
115. Griffin FM, Scuderi GR, Insall JN, et al. Total knee arthroplasty in patient who were obese with 1 years followup. *Clin Orthop.* 1998;356:28–33.
116. Mont MA, Mathur SK, Krackow KA, et al. Cementless total knee arthroplasty in obese patients. A comparison with a matched control group. *J Arthroplasty.* 1996;11(2): 153–156.
117. Spicer DD, Pomeroy DL, Badenhausen WE, et al. Body mass index as a predictor of outcome in total knee replacement. *Int Orthop.* 2001;25(4):246–249.
118. Wendelboe AM, Hegmann KT, Biggs JJ, et al. Relationships between body mass indices and surgical replacement of knee and hip joints. *Am J Prev Med.* 2003;25(4):290–295.
119. Vazquez-Vela Johnson G, Worland RL, Keenan J, et al. Patient demographics as a predictor of the ten-year survival rate in primary total knee replacement. *J Bone Joint Surg Br.* 2003;85(1):52–56.
120. Blunn GW, Walker PS, Joshi A, et al. The dominance of cyclic sliding in producing wear in total knee replacements. *Clin Orthop.* 1991;273:253–260.
121. Kawanabe K, Clarke IC, Tamura J, et al. Effects of A-P translation and rotation on the wear of UHMWPE in a total knee joint simulator. *J Biomed Mater Res.* 2001;54(3): 400–406.
122. Rose RM, Goldfarb HV. On the pressure dependence of the wear of ultrahigh molecular weight polyethylene. *Wear.* 1983;92:99–111.
123. Rostoker W, Galante JO. Contact pressure dependence of wear rates of ultra high molecular weight polyethylene. *J Biomed Mater Res.* 1979;12:957–964.
124. Sathasivam S, Walker PS. A computer model with surface friction for the prediction of total knee kinematics. *J Biomechanics.* 1996;30(2):177–184.
125. Szivek JA, Anderson PL, Benjamin JB. Average and peak contact stress distribution evaluation of total knee arthroplasties. *J Arthroplasty.* 1996;11(8):952–963.
126. Wimmer MA, Andriacchi TP. Tractive forces during rolling motion of the knee: implications for wear in total knee replacement. *J Biomechanics.* 1996;30(2):131–137.
127. Wimmer MA, Andriacchi TP, Natarajan, et al. A striated pattern of wear in ultrahigh-molecular-weight polyethylene components of Miller-Galante total knee arthroplasty. *J Arthroplasty.* 1998;13(1):8–16.
128. Booth RE Jr. Total knee arthroplasty in the obese patient: tips and quips. *J Arthroplasty.* 2002:17(4)(Suppl 1):69–70.
129. Tradonsky S, Postak PD, Froimson AI, et al. A comparison of disassociation strength of modular acetebular components. *Clin Orthop.* 1993;296:154–160.
130. Halley D, Glassman A, Crowninshield RD. Recurrent dislocation after revision total hip replacement with a large prosthetic femoral head. *J Bone Joint Surg Am.* 2004; 86(4):827–830.
131. Ries MD. Dissociation of an ultra-high molecular weight polyethylene insert from the tibial baseplate after total knee arthroplasty. *J Bone Joint Surg Am.* 2004;86(7): 1522–1524.
132. Blunn GW, Joshi AB, Minns, et al. Wear in retrieved condylar knee arthroplasties. *J Arthroplasty.* 1997;12(3):281–290.
133. Jasty M, Goetz DD, Bragdon CR, et al. Wear of polyethylene acetabular components in total hip arthroplasty. an analysis of one hundred and twenty-eight components retrieved at autopsy or revision operations. *J Bone Joint Surg Am.* 1997;79(3):349–358.
134. Landy MM, Walker PS. Wear of ultra-high-molecular-weight polyethylene components of 90 retrieved knee prostheses. *J Arthroplasty.* 1988;3(Suppl):S73–85.
135. Ries MD, Scott ML, Jani S. Relationship between gravimetric wear and particle generation in hip simulator: conventional compared with cross-linked polyethylene. *J Bone Joint Surg.* 2001;83(Suppl 2, Pt 2):116–122.
136. Ingram JH, Fisher J, Stone M, et al. Effect of crosslinking on biological activity of UHMWPE wear debris. *Trans Orthop Res Soc.* 2003;28(2):1439.
137. Scott ML, Ries MD, Jani S. Abrasive wear in total hip replacement: is crosslinked UHMWPE coupled to ceramic heads the answer? *Proc Am Acad Orthop Surg.* 2002;3:732.
138. Muratoglu OK, Burroughs BR, Christensen SD. In vitro simulator wear of highly crosslinked tibias articulating against explanted rough femoral components. *Trans Orthop Res Soc.* 2004;29(1):297.
139. Good V, Ries M, Barrack RL, et al. Reduced wear with oxidized zirconium femoral heads. *J Bone Joint Surg Am.* 2003;85(Suppl 4):105–110.
140. Laskin RS. An oxidized Zr ceramic surfaced femoral component for total knee arthroplasty. *Clin Orthop.* 2003;416: 191–196.