

Revision Total Knee Arthroplasty

James V. Bono
Richard D. Scott
Editors

Third Edition

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 Springer

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Preface

Revision total knee arthroplasty was initially created as a “how-to” text for the diagnosis and management of the failed total knee arthroplasty, with step-by-step descriptions of surgical techniques of revision total knee arthroplasty. The second edition has become a practical reference for students, residents, fellows, and attending surgeons engaged in the treatment and follow-up of patients who have undergone knee replacement surgery, with over 34,000 downloads worldwide.

In the third edition, Part I covers the evaluation and diagnosis of the failed total knee arthroplasty including an update on the current incidence and reasons for the need for reoperation after total knee arthroplasty.

Part II emphasizes the general principles of revision surgery technique, including management of skin, surgical exposure, and removal of femoral and tibial implants at the time of revision. The fundamental aspects of the restoration of deficient bone stock, proper alignment, and adequate fixation are thoroughly discussed.

Part III discusses special considerations including the topics of infection, periprosthetic fracture, and stiffness and discusses the complexities of total knee arthroplasty after failed high tibial osteotomy, after fractures about the knee, and after prior unicompartmental and hinged knee replacement. The topics of insert exchange, aseptic synovitis, and the economics of revision total knee arthroplasty are discussed individually, as well as the role of arthrodesis as a salvage procedure.

Part IV is dedicated to technology and includes the role of robotics in revision TKA, sensor technology, mixed reality, and smart implants. The role of patient specific, aka custom implants, is discussed, highlighting the creativity of revision surgeons and the ingenuity of biomedical engineering. And finally, as we enter the Information Age, the state of digital technology is reviewed, along with the ramifications of patient monitoring, data access, privacy, cloud connectivity, artificial intelligence, and machine learning.

We feel fortunate to have received the support of so many well-known master surgeons who have contributed to the text. We are grateful to all of them and are honored to have been able to present their combined experience in the ensuing pages.

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Part I

Diagnosis and Evaluation of Revision Total Knee Arthroplasty

Reoperation After Total Knee Arthroplasty

1

Richard D. Scott

The specific incidence of and causes for reoperation after total knee arthroplasty (TKA) continue to change with time. In the early experience with hinge and condylar knees, reoperations were most frequently required for prosthetic loosening, knee instability, and sepsis. Thirty-five years ago, patellofemoral complications accounted for up to 50% of reoperations [1]. With improved prosthetic designs and better surgical techniques, reoperations became less frequent. In the decade between 2000 and 2010, polyethylene wear (often associated with lysis) was a leading cause of failure [2]. With improvements in polyethylene fabrication, sterilization methods, and modular locking mechanisms, this failure mode has become less common.

In this chapter, the arthroplasty literature will be reviewed for updated reports of the current modes of failure of TKA [3–17]. These reports will highlight the reasons for revision, but most of them cannot give an incidence or annual failure rate since they do not include the size of the population from which the failures occurred.

To address the issue of incidence and annual failure rate, my personal incidence and causes of reoperation after 4993 consecutive posterior cruciate ligament (PCL)–retaining primary TKAs

followed for a mean of 15 years are presented. Among these, there were 264 knees requiring reoperations. Some causes are obviously prosthesis-specific. Nevertheless, this experience will help to give an overview of the incidence and causes of re-operation likely to be seen today in a total knee arthroplasty practice and also provide a calculated annual re-operation rate.

Literature Review

According to published reports between 2011 and 2022, the reasons for TKA reoperation have continued to evolve, but less slowly than in the prior decade. All reports note a decreasing incidence of polyethylene wear as a causative factor. Some studies separate failures into early and late, with “early” defined as within 2 years of the arthroplasty implantation and “late” as any time after that date.

Le et al. reviewed all first-time revisions performed at one institution over a 10-year period [3]. These included both referred cases as well as those originally operated at their institution. Forty-six percent of the revisions were in the “early” group while 54% were operated beyond their 2-year anniversary. In the early group, reasons for revision in decreasing frequency were instability (26%), infection (24%), stiffness (18%), and poly wear (2%). In the late group, the

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reasons were infection (25%), instability (18%), stiffness (14%), and poly wear (9%).

Zmitkowski et al. reported an 8-year experience at one institution with 10,188 primary TKAs documenting only those cases that required an operating room anesthetic but did not require a component revision [4]. Follow-up was 1–9 years with a median of 4 years. Four percent of knees required a “surgical intervention” for a rate of 1% per year. Reasons for reoperation in decreasing order of frequency included manipulation for stiffness (58%), patellar clunk (12%), infection (12%), incision complications (6%), and hematoma (4%). If the manipulations for stiffness were eliminated, the reoperation rate would be slightly less than 0.5% per year.

Thiele et al. conducted a retrospective study that included all first revisions performed at 2 high volume arthroplasty centers between 2005 and 2010 where at least one prosthetic component was replaced [5]. Of 358 revisions, 20% were performed within the first year. The most common indications for reoperation within the first year were infection (27%) and instability (24%). Between 1 and 3 years, malalignment (29%) and instability (23%) were most frequent. Beyond 3 years, aseptic loosening (35%), instability (19%), and polyethylene wear (19%) were most common.

Sharkey et al. reviewed 781 revision cases and compared the reasons for reoperation to a report from the same institution 10 years prior [6]. It was noted that besides wear being less frequent, infection was the most common cause for early failure while aseptic loosening predominated in late failures.

Schroer et al. and Lombardi et al. both reported on 844 revisions performed between 2010 and 2011 at several centers [7, 8]. Thirty-five percent of revisions occurred “early” and appeared to be surgeon-dependent. Overall failure reasons included loosening (31%), instability (19%), infection (16%), stiffness (10%), and malalignment (7%). They also noted that unexplained pain accounted for some revisions in their as well as most reported series.

Dalury et al. studied 820 revisions performed between 2000 and 2012 [9]. Loosening, infec-

tion, instability, and wear accounted for approximately 20% each of reoperations, but they noted that wear-related failures were less frequent in the more recently operated patients.

More recently published articles confirm that mechanical loosening and infection remain the most prevalent causes for failure [10, 11] with infection and the main reason for re-revision [11].

Abdel’s group at the Mayo Clinic studied failure ideologies for primary posterior-stabilized knee arthroplasties and separated their findings into the operations that did or did not require component revision [12]. For those not requiring component revision, stiffness (58%), and delayed wound healing (21%) predominated followed by operative intervention for patellar clunk syndrome [13]. Once the ideology of this patellar clunk was established, posterior stabilized components were re-designed to improve the transition of the patellar tracking from the trochlea groove onto the femoral condyles minimizing its current incidence. Their same study found that the most common reasons for re-operation when the component revision was required were infection in 52% of cases, aseptic loosening in 17%, and periprosthetic fracture or instability in 10% of cases.

Causes for revision will differ at referral centers that specialize in taking care of failed arthroplasties. Poster and colleagues assessed 312 patients who underwent 402 revision knee arthroplasty’s [14]. Ninety percent of these patients were referred to them while 10% were among their patients. Twenty-eight percent of the referrals had already undergone a revision procedure before presenting at their center. The most frequent reason for revision was infection in 36% followed by aseptic loosening in 22% and periprosthetic fracture in 14%.

Repeat Revision

Reasons for repeat revision are different than those for an initial revision. Meyer et al. noted that infection at 40%, periprosthetic fracture at 26% and aseptic loosening at 14% were the

leading causes of failure after a revision arthroplasty [15]. Survivorship of the revision procedures was 93% at 2 years and 83% at eight years.

Prosthesis Specific Issues

Certain reasons for knee replacement failure can be prosthesis specific (other than that described above regarding patella clunk syndrome). There have been some reports of component-cement interface loosening (referred to as debonding) as a result of the surface finish of the metallic component lacking sufficient roughness to bond adequately with the cement. These design issues can easily be resolved when fabrication methods are modified appropriately and should not be thought of as failure methods generic to knee arthroplasty.

Summary

In summary, infection, loosening, and instability remain the most frequent reasons for revision after total knee arthroplasty with infection predominating early and prosthetic loosening and instability becoming more frequent over time. Polyethylene wear is still a factor but is occurring with much less frequency than it did in prior years.

A Single Surgeon’s Reoperation Experience from a Computerized Database

In November of 1984, a database was established to follow consecutive posterior cruciate-retaining primary knee arthroplasties performed by one surgeon. Data were maintained in a computerized database. Patient demographics, operative details, follow-up examinations, and reoperations were monitored and documented. As of January, 2016, 4993 knees were included in the database with 264 knees requiring a reoperation (Table 1.1). The following is a review of the causes and incidence of first-time reoperations including a cal-

Table 1.1 264 reasons for reoperation on 4993 knees (mean 15-year follow-up)

94 insert wear with lysis (most implanted in mid 1990s)
37 insert wear with synovitis
8 insert wear without symptoms
32 late metastatic infections
13 stiffness (8 treated with arthroscopy)
9 metal-backed patellar wear (10% at mean 28 year FU)
8 broken porous femoral components (none since 1996)
8 atraumatic laxity (involving insert exchange)
7 unresurfaced patellar pain (4% at mean 20 year FU)
7 loose cemented femoral components (among 3448 = 0.20%)
6 recurrent rheumatoid synovitis (among 244 rheumatoid knees) 6 loose cemented tibial components (among 4953 = 0.12%)
5 recurrent hemarthrosis
4 shear-off patellar lugs 4 loose cementless tibias (10% at mean 25 year FU) 3 traumatic laxity (involving insert exchange) 3 ganglion cysts 3 patellar loosening (among 4815 = 0.06%) 2 loose cementless femoral components (among 1378 = 0.15%) 1 patellar clunk 1 rotating bearing spin-out (among 820 = 1%) 1 traumatic fracture of tibial bone involving need for revision 1 traumatic fracture of femoral bone involving need for revision 1 fractured resurfaced patellar bone involving component removal

culated annual reoperation rate. Patients were urged (and constantly reminded) to report any surgical interventions performed elsewhere. Despite this, it is possible that an occasional reoperation performed elsewhere has not been included in the statistics.

Infection

Early operative infection should be a rare occurrence today with the use of improved sterile technique, more efficient surgery with shorter operating times, and peri-operative antibiotics. Most surgeons should experience an early operative infection rate between 0 and 0.3%. Infection is most likely to occur in the multiply-operated, diabetic, or morbidly obese patient or when there has been a wound healing issue. Many factors likely accounted for the low (0%) primary infection rate in this series [18].

Late metastatic infection from a remote focus can occur throughout the life of the patient [19]. Common sites that can cause bacteremia that

seeds the joint are the oral cavity, gastrointestinal and urinary tract or skin site (usually cellulitis). Some of these cases are inevitable despite the education of patients and treating physicians about their possibility. They are currently responsible for about 12% of re-operations (32 among the 264 knees re-operated in this series) and may eventually become the leading cause as other issues are minimized. The incidence of late metastatic infection was 0.6% at a mean follow-up of 15 years with an occurrence rate of 0.04% per year of follow-up.

Patients must be educated as to the prevention of late infections and dental procedures occurring in the face of infected tissue must have antibiotic coverage. Dental prophylaxis for routine procedures has become controversial and is not advocated as much as it was in prior years.

Femoral Component Loosening

Isolated femoral component loosening has been very rare in this series whether the component was cemented or cementless. Failure of either femoral fixation method accounted for approximately 3% of re-operations. The incidence of femoral loosening was 0.2% at a mean 15-year follow-up occurring at a rate of 0.01% per year.

The success of a cementless femur is likely dependent on the quality of primary fixation at the time of the arthroplasty. In this series, suitability for cementless fixation was subjectively determined by testing the difficulty of removing the femoral trial using an extractor with a slap-hammer.

Both cemented and cementless femurs are vulnerable to late loosening in the presence of severe osteolysis and this data is included in the section on wear and lysis.

Tibial Component Loosening

Isolated cemented tibial component loosening is also infrequent and also accounts for approximately 2% of re-operations. It also has an extremely low incidence of 0.01% per year fail-

ure over the first 15 years. As seen on the femoral side, tibial loosening is more prevalent in the presence of wear debris-induced osteolysis.

Cementless tibial components are more likely to loosen than cemented components with the incidence dependent on their design and the accuracy of implantation. Components fixed with screws or those using metals with high ingrowth potential are more likely to enjoy long-term success. In this series, there were only 40 cementless porous titanium tibias implanted, none with screw fixation. At a mean 25-year follow-up, 4 had loosened for an incidence of 10%. Conclusions about the success of cementless tibial fixation using current designs cannot be judged by the results in this series because of the outdated design.

Patellar Complications

As mentioned earlier, patellar problems were the leading cause of re-operation in the late 1980s. These complications included worn metal-backed patellar components, patellar fracture when large central fixation lugs were in vogue, and patellar loosening when fixation was via a small central fixation lug. Since the mid-1980s three-pegged polyethylene patellar components (as were used in this series) became the state of the art. Metal-backed patellar components were abandoned in this series in 1986. Of 87 implanted, 9 had worn through and required revision [20].

With the three-lugged fixation method, both loosening and fractures were rare. Of 4699 all-poly 3-lugged patellas implanted, there were 3 reoperations for loosening, 1 for a fracture, and 1 for a patellar clunk. Shearing-off of the 3 lugs occurred in 4 cases with an early design. Its etiology required the presence of an abnormal shearing force caused by the imbalance in the quadriceps mechanism. The conformity of the prosthetic articulation tended to keep the patella located in the trochlear groove while the soft tissue imbalance pulled the patella toward the lateral side, resulting in the shear forces. Once the junction between the lug and the patellar compo-

ment was reinforced by a design change, this complication has not been seen.

A few traumatic fractures of the body of the patella occurred, but were treated conservatively and did not require surgery. Small avulsion fractures that usually involved a few millimeters of the superior pole of the patella were also seen, often as rare incidental findings noted at routine follow-up. Occasionally, they were symptomatic for approximately 6 weeks during which time the patients were advised to avoid high forces across the patellofemoral articulation such as ascending stairs and arising from a sitting position without arm support.

Early in this series, patellas were selectively left un-resurfaced based on the findings of non-inflammatory arthritis, less than grade III cartilage degeneration, and congruent tracking with the trochlear flange [21]. Approximately 20% of osteoarthritic patients met these criteria. In the last 2 decades, the long-term success of 3 pegged all poly patellar components led to almost universal patellar resurfacing except for the rare young, heavy and active male patient. Using these criteria, 178 un-resurfaced patellas have a mean follow-up of 20 years. Of these, 7 (4%) have required secondary resurfacing.

Overall, patellar problems account for 6% of re-operations and occur at a rate of 0.4% per year.

Polyethylene Wear and Lysis

In the 1990s, polyethylene wear (and its consequences) was the most frequent cause of reoperation after TKA. Wear can present as an isolated radiographic finding or can produce symptomatic wear-debris synovitis and eventual osteolysis that can compromise prosthetic fixation. Polyethylene wear complications accounted for a little over 50% of re-operations in the early 2000s [2]. Of these, approximately two-thirds were associated with lysis, one-third with synovitis only and between 5 and 10% presented with asymptomatic radiographic wear at a routine follow-up that was severe enough to warrant an elective insert exchange. The chance of requiring an operation for a wear-related problem ran

approximately 0.25% per year of follow-up for the first 27 years. Almost all wear-related problems were seen in modular tibial components. All-poly non-modular tibial components when used in elderly patients have few if any wear-related issues and tend to outlive the patient.

Osteolysis was extremely rare in knees implanted in the 1980s. Its incidence began to slowly climb in the early 90s and may have peaked in knees implanted in the late 1990s. The reasons for this are multi-factorial. Inserts implanted in that era were still gamma-radiated in the air (the state of the art at that time). In addition, more conforming articulations started to be used to decrease topside wear. These conforming articulations can transfer stresses away from the topside to the insert-tray interface possibly leading to increased backside wear and the fine debris particles that incite the lytic process [22]. The confounding issue of dealing with topside wear via increased conformity but precipitating backside wear because of force imparted to the insert tray interface can be addressed by rotating bearing components or by the use of non-modular metal-backed or all polyethylene components. Modern systems also tend to have better locking mechanisms and many have polished trays to minimize backside wear caused by micro-motion. Polyethylene itself, also continues to undergo fabrication modifications to eliminate oxidation and improve wear characteristics.

In this series, there were 139 wear-related failures accounting for 53% of the reoperations. Ninety-four were for lysis, 37 for synovitis, and 8 showed asymptomatic wear on routine follow-up radiographs. Their incidence diminished yearly as a result of the fabrication and prosthetic design improvements noted above.

Miscellaneous Causes of Re-operation

There are a number of miscellaneous causes of reoperation after TKA that together account for approximately 15% of re-operations (Table 1.1). These include ankylosis that doesn't respond to closed manipulation, traumatic and atraumatic

instability, recurrent hemarthrosis [23], recurrent rheumatoid synovitis, and symptomatic ganglion cysts that tend to arise from the proximal tibiofibular joint [24].

Summary

In summary, PCL retaining fixed-bearing TKA can be a highly successful operation with the need for more surgery in the author's experience occurring at the rate of approximately 0.35% per year over the first 30 years of follow-up. The most common cause for revision surgery in this series was related to polyethylene insert failure in knees operated in the early 1990s.

Regarding reoperation statistics reported in the recent literature, it is noted that wear-related problems are less frequent than in prior years while infection, loosening, instability, and stiffness now predominate.

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Implant Bearings in Total Knee Arthroplasty

2

Christine S. Heim and A. Seth Greenwald

The Enduring Goal

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 2022 almost 2.1 million primary and revision hip and knee arthroplasty procedures were performed in the United States, a number more than doubling on a global basis [1] (Table 2.1). Improvements in surgical technique and implant design over the last five decades have resulted in total knee arthroplasty (TKA) being deemed one of the most successful, contemporary orthopedic procedures to effectively relieve pain and allow patients to resume the activities of their daily lives. The prevalence of aseptic loosening attributed to ultra-high molecular weight polyethylene (UHMWPE) wear debris-induced osteolysis is in the single digits in most knee series, with some reports describing prosthesis survival beyond 20 years [2–25]. Despite this obvious success, UHMWPE wear is an inescapable consequence of total joint articulation and is of contemporary concern particularly as our population grows and lifestyle demands increase [26–46]. Appreciating an orthopedic triad where patient outcomes are not only dictated by the implant but

Table 2.1 Hip and knee arthroplasty procedures performed in the United States in 2022

	Primary	Revision	Total
Knees	1,168,772	130,312	1,299,084
Hips	687,633	77,925	765,558
Total	1,856,405	208,237	2,064,642

Data from *Orthopedic Network News* [1]

are highly dependent on patient factors and technical proficiency assists the goal of avoiding total knee arthroplasty revision.

An Orthopedic Triad: The Implant

The Evolution of UHMWPE Ultra-high Molecular Weight Polyethylene (UHMWPE)

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 1020 and GUR 1050 are the prevalent polymers utilized 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 [47]. While UHMWPE has remained the tibial insert and patellar component-bearing

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Fig. 2.1 A 5-year retrieval of a failed poly-II tibial insert demonstrating a high component wear rate with infiltration of carbon fibers and polyethylene debris into surrounding tissue

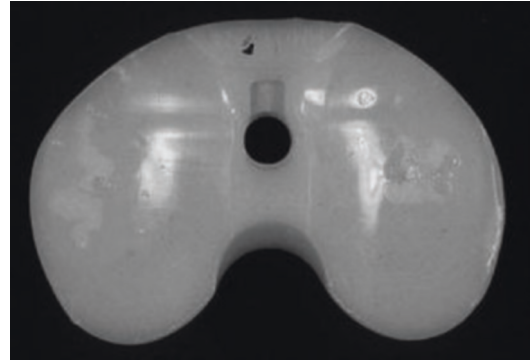


Fig. 2.2 A 3-year retrieval of a failed Hylamer-M tibial plateau demonstrating an unexpectedly high wear rate with corresponding wear and debris-induced inflammatory tissue response

material of choice over the last five decades, researchers are continually striving to increase its in-vivo longevity through alterations to processing and/or sterilization techniques.

Short- to mid-term clinical reports of UHMWPE damage in the 1990s led to a review of manufacturing processes and determined that inadequate quality control resulted in fusion defects arising from incomplete polymerization, voids, and foreign body inclusions [48–50]. Recognizing the direct impact of these variables on the in-vivo degradation of the final parts, orthopedic device manufacturers addressed the allowable tolerances for these components, and these issues have not reappeared in the peer-reviewed literature.

Previous attempts to improve UHMWPE performance have included carbon fiber reinforcement (Poly-II) [51] and polymer reprocessing by hot isostatic pressing (Hylamer) [52]. The former was withdrawn from the market because of an unexpectedly high wear rate [53] (Fig. 2.1), while the latter has been linked to debris-induced osteolytic response, especially when sterilized by gamma irradiation in air [54] (Fig. 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 [55] (Fig. 2.3). These material innovations had checkered pasts as they moved from the laboratory to clinical application.

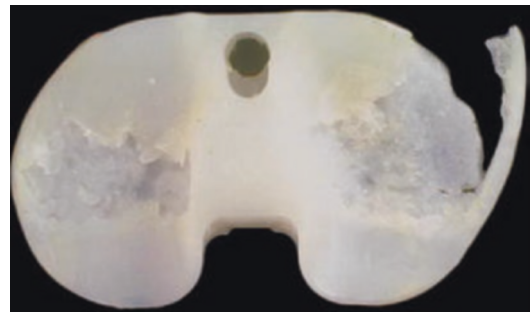


Fig. 2.3 A 6-year retrieval of a heat-pressed tibial component associated with polyethylene fatigue and early delamination

Gamma irradiation in air was the predominant method of UHMWPE component sterilization, and, to this day, represents the long-term standard against which contemporary material improvements are measured. In the early 1990s, an increasing prevalence of tibial component failures associated with debris-induced osteolysis raised concerns over the long-term durability of contemporary devices [56, 57]. A clinical follow-up study reported by Bohl et al. suggested that this may be accounted for by the prolonged shelf storage prior to implantation of UHMWPE components gamma irradiated in air [58]. A 12–20% reduction in in-vivo survival was noted for shelf storage ranging from 4 to 11 years with a mean in-vivo time to revision of 2.5 years (Figs. 2.4 and 2.5).

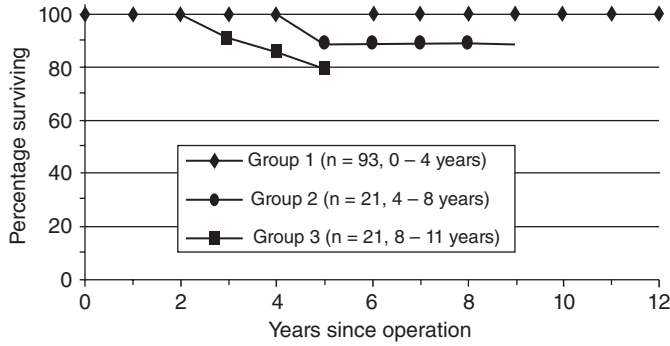


Fig. 2.4 The influence of shelf storage on survival of a prosthetic knee plateau following gamma irradiation in air (from Bohl JR, Bohl WR, Postak PD, et al. The effects of

shelf life on clinical outcome for gamma sterilized polyethylene tibial components. Clin Orthop Relat Res. 1999;267:28–38, with permission)

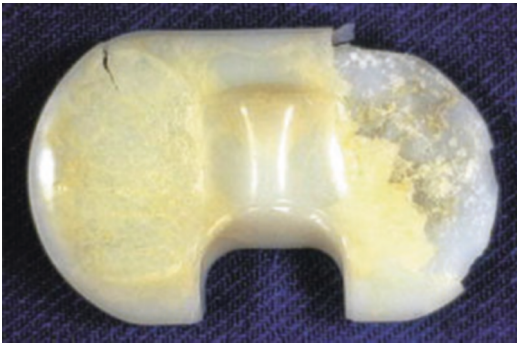


Fig. 2.5 A group 2 plateau implanted after 7.6 years of shelf storage and retrieved 3.8 years after implantation. Gross delamination and pitting, characteristics of fatigue failure, are observed (from Bohl JR, Bohl WR, Postak PD, et al. The effects of shelf life on clinical outcome for gamma sterilized polyethylene tibial components. Clin Orthop Relat Res. 1999;267:28–38, with permission)

Further, laboratory studies indicated that as shelf storage increased, the amount of UHMWPE exposed to high surface stresses during articulation increased dramatically and was a contributing factor to early in-vivo polymer failure [59–61] (Fig. 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 [62, 63] (Fig. 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 consid-

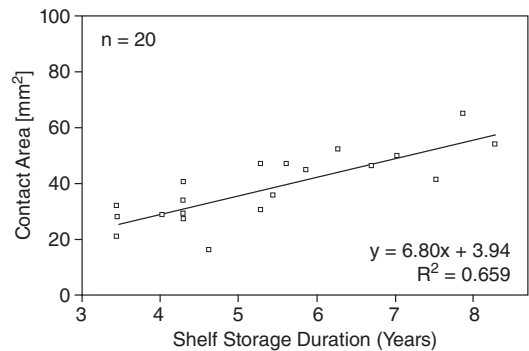


Fig. 2.6 Tibial-femoral contact area for a 5.6-mm thick tibial plateau carrying >20 MPa stresses during articulation dramatically increases with lengthening shelf storage periods

eration, but ongoing shelf life oxidation offered an explanation for the mechanical compromise of the polymer in-situ [60, 62, 64, 65] (Fig. 2.8). It is also noted that in-vivo component oxidation continues after implantation, but to a lesser degree [66].

At this point, attempts to remove oxygen from the sterilization process included the use of inert gas and vacuum environments or by avoiding gamma irradiation altogether through the use of ethylene oxide (EtO) or gas plasmas [67–69]. Acetabular components sterilized by these techniques demonstrated a reduction in UHMWPE wear in hip simulation studies (Fig. 2.9). Today, orthopedic device manufacturers avoid the use of an air environment when packaging UHMWPE components, and sterilization dates are standard on the device package labeling.

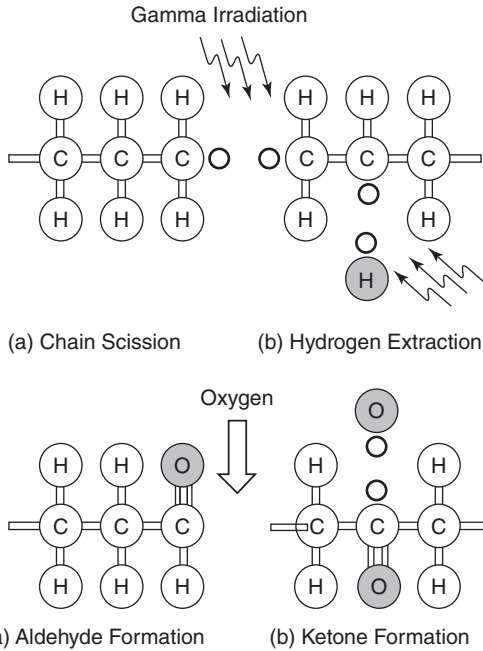


Fig. 2.7 Depicted polymer chain breakage following irradiation in air and combination with oxygen facilitating oxidative degradation of UHMWPE

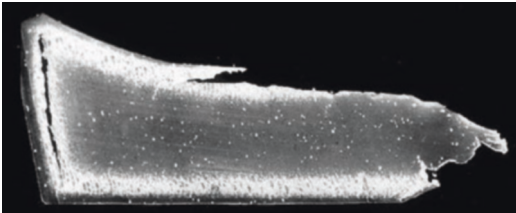


Fig. 2.8 A 3-year retrieval of a fully oxidized, gamma irradiated in air, UHMWPE tibial component demonstrating a circumferential white band indicative of polymer embrittlement after prolonged shelf life. Fusion defects from incomplete consolidation are noted

It is now also 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 cross-links between the molecules of adjacent chains, which is further enhanced in an oxygen-free environment [70–72]. Figure 2.10 from McKellop et al. [71] is descriptive of this phenomenon in a simulator comparison of acetabular cup components with the volumetric wear per million cycles dramatically reduced with increasing gamma radiation exposure.

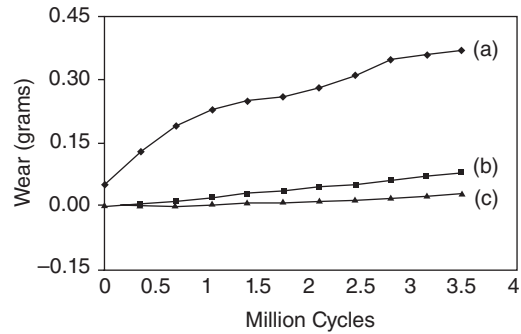


Fig. 2.9 Hip simulator weight-loss comparison for aged (25 days at 78 °C in O₂) compression-molded cup components: (a) gamma irradiated in air; (b) sterilized with ethylene oxide; and (c) gamma irradiated in a vacuum environment and use of barrier packaging. (From Greer et al. [68] by permission of *Trans Orthop Res Soc*)

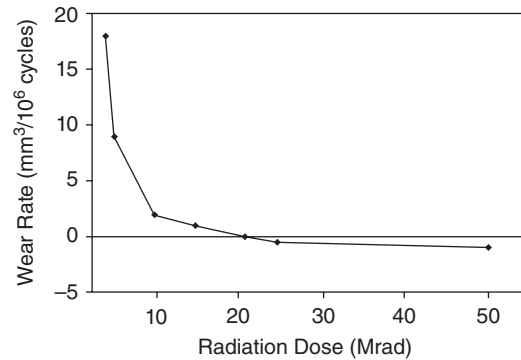


Fig. 2.10 Mean acetabular cup wear rates versus gamma dose level (from McKellop H, Shen FW, Lu B, et al. Development of an extremely wear-resistant ultra-high molecular weight polyethylene for total hip replacements. *J Orthop Res.* 1999;17(2):157–167, with permission)

There are clinical reports attributed to Oonishi and Grobbelaar, which describe in-vivo UHMWPE wear reduction in acetabular components realized through increased cross-linking [73–78]. 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 [79].

These isolated studies pointed the way to a new class of UHMWPEs, whose common denominator was an appreciation of the importance of increased cross-linking while minimiz-



Fig. 2.11 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 S, Postak PD, Froimson AI, et al. A comparison of disassociation strength of modular acetabular components. Clin Orthop Relat Res. 1993;296:154–160, with permission)

Table 2.2 Moderately to highly cross-linked UHMWPEs

Manufacturer	UHMWPE trade name
Biomet	ArComXL
DePuy/J&J	Marathon AltrX
Smith + Nephew	XLPE
Stryker	Crossfire X3
Zimmer	Durasul Longevity Prolong

ing oxidative degradation to reduce wear. Initial methods used to manufacture these moderately to highly cross-linked UHMWPEs included (1) heating above or below the melt temperature of the polyethylene, (2) the type of radiation employed, (3) the radiation dose level, (4) the sequence of stepwise application, and (5) the endpoint sterilization. The one common factor is that radiation was integrated into the manufacturing process. All received U.S. Food and Drug Administration 510[k] clearance, allowing commercial distribution for both hip and knee components (Table 2.2).

However, changes in the mechanical properties of these materials, particularly in their reduced resistance to fatigue crack propagation (fracture toughness), raised concerns about their long-term suitability in hip and knee compo-

nents where locking mechanisms offered foci for stress risers [80–83] (Figs. 2.11, 2.12, and 2.13). Short-term clinical reports for total hip arthroplasty demonstrated a significant reduction in wear volume and rate for these polymers [84–89], which supported the impressive pre-



Fig. 2.12 A 10-month 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 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, with permission)

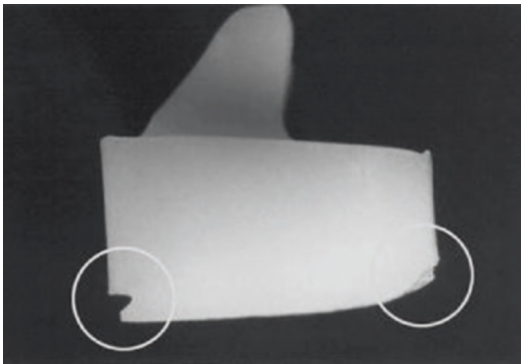


Fig. 2.13 A 3-year failure of a constrained condylar conventional UHMWPE tibial insert. Failure of the posterior locking mechanism resulted in posterior component lift-off (from Ries MD. Dissociation of an ultra-high molecular weight polyethylene insert from the tibial baseplate after total knee arthroplasty. J Bone Joint Surg Am. 2004;86(7):1522–24, with permission)

clinical hip simulation laboratory data [90–94]. However, the negative impact of extreme component positioning on outcome was also demonstrated through case and retrieval reports at this time [82, 95, 96].

An appreciation of the differing modes of hip (abrasion and adhesion) and knee (pitting and delamination) failure, confirmed through conventional UHMWPE component retrieval [97–99], also suggested that a universal, moderately to highly cross-linked polymer may not be appropriate. To counter the reported degradation in material properties, “enhanced” UHMWPEs now have antioxidants, predominantly vitamin E, infused or blended into the resin powder during the manufacturing process (Table 2.3). Laboratory studies have confirmed the maintenance of UHMWPE mechanical properties and wear resistance in addition to prevention of oxidative degradation for these polymers [100–107].

Contemporary peer-reviewed literature for the moderately to highly cross-linked UHMWPEs in total hip arthroplasty is reporting a dramatic reduction of wear rate when compared to conventional UHMWPE in mid- to long-term follow-up studies with metal femoral heads [108–124]. Total knee arthroplasty clinical reporting focuses on aseptic loosening and mechanical failures rather than wear rate, but again, in short- to mid-term studies, these UHMWPEs are demonstrating efficacy with no revisions due to osteolysis [125–131]. While short- to mid-term clinical studies supporting the further advantages of the antioxidant-infused UHMWPEs in total hip arthroplasty are increasing [132–142], reporting for total knee arthroplasty has just begun [143–145]. While the overall clinical gains of

these enhancements have been questioned [146–148], the passage of in-vivo time will be, as has always been, the defining factor in the continued use of these moderately to highly cross-linked UHMWPEs with or without antioxidants.

The Femoral Side

While the predominant focus for increasing the in-vivo longevity of total knee arthroplasty is alteration of the UHMWPE tibial insert, there are alternative bearing options for the femoral component as well. As example, oxidized zirconium, marketed under the trade name Oxinium (Smith + Nephew, Memphis, TN) in the United States, has the strength of metallic cobalt-chromium femoral components with the wear characteristics of ceramics [149], as has been shown in laboratory simulators for pairings with both conventional and highly cross-linked UHMWPE [150, 151]. The uniqueness of this material is that it offers patients with metal hypersensitivity, particularly to nickel, an implant option that has been shown to be clinically equivalent to cobalt-chromium femoral components [152–157].

The Tibial-Femoral Geometries

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 [56]. The ability of a given design to minimize contact stresses during walking gait contributes to UHMWPE tibial component longevity [158]. With this, 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 [159] (Fig. 2.14).

Table 2.3 Contemporary antioxidant-infused UHMWPEs

Manufacturer	UHMWPE trade name
Corin	ECiMA
DePuy Synthes	AOX
Enovis	E+
MicroPort Orthopedics	E-Class
Zimmer Biomet	Vivacit-E E1

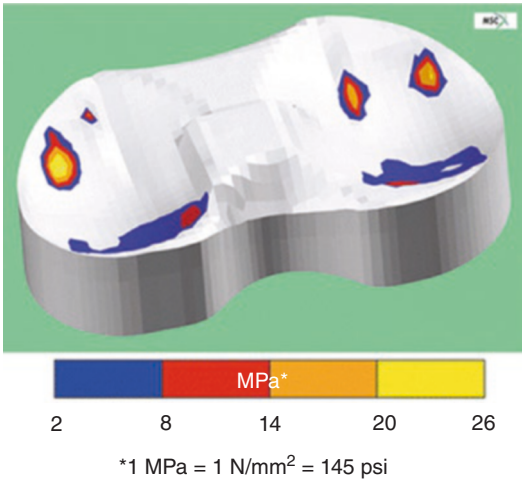


Fig. 2.14 Finite element analysis of tibial-femoral contact areas and surface stresses of a contemporary mobile bearing knee design at 0° extension. Poor mating of the articulating surfaces is observed resulting in peripheral contact with damaging stress levels

The attainment of femoral component tolerances has markedly improved with the 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 (Fig. 2.15). The implications of this technique have potentially far-reaching consequences. As design specifications are produced with tighter tolerances, the need for precision manufacturing is imperative (Fig. 2.16).

The Wear Particles

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 [160] (Figs. 2.17 and 2.18). The greatest potential for cytokine release, the first step in the sequelae leading to osteolysis, following macrophage debris encapsulation is at the <1 µm level. Ingram et al. suggested that highly cross-linked UHMWPE debris obtained from

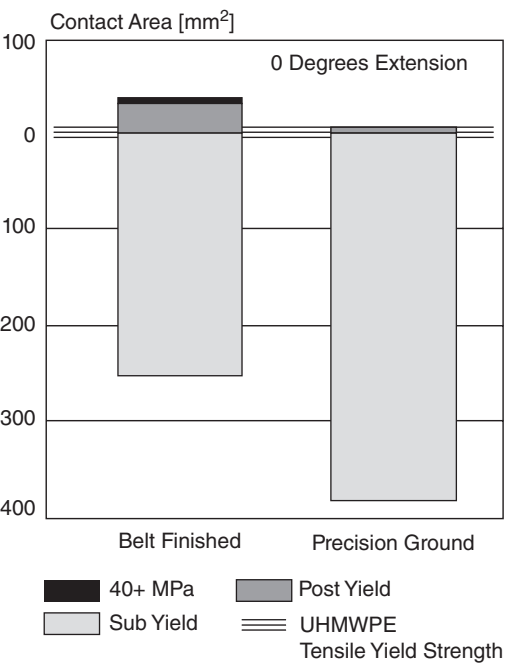


Fig. 2.15 A comparison of tibial-femoral contact areas by surface stress range for belt finishing and computer-aided precision grinding techniques of a single femoral component design at 0° extension. The overall bar height depicts the total contact area (from Heim CS, Postak PD, Greenwald AS. Factors Influencing the longevity of UHMWPE tibial components. In: Pritchard D, editor. Instructional Course Lectures, vol 45. Chicago, IL: American Academy of Orthopaedic Surgeons; 1996, with permission)

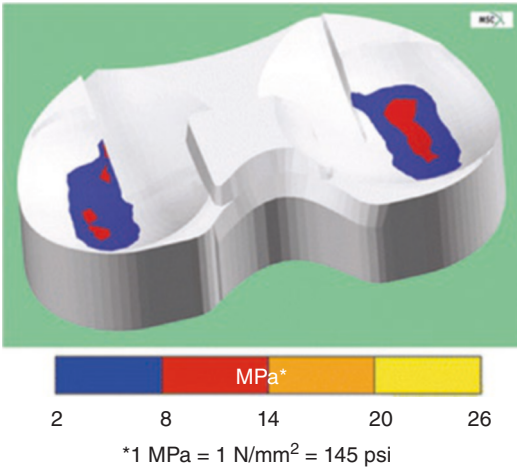


Fig. 2.16 Finite element analysis demonstrating the optimization of tibial-femoral contact areas and surface stresses resulting from quality controlled finishing of the component demonstrated earlier in Fig. 2.14. It is apparent that the use of the conforming geometries has been achieved with the resulting diminishment of peak contact stresses

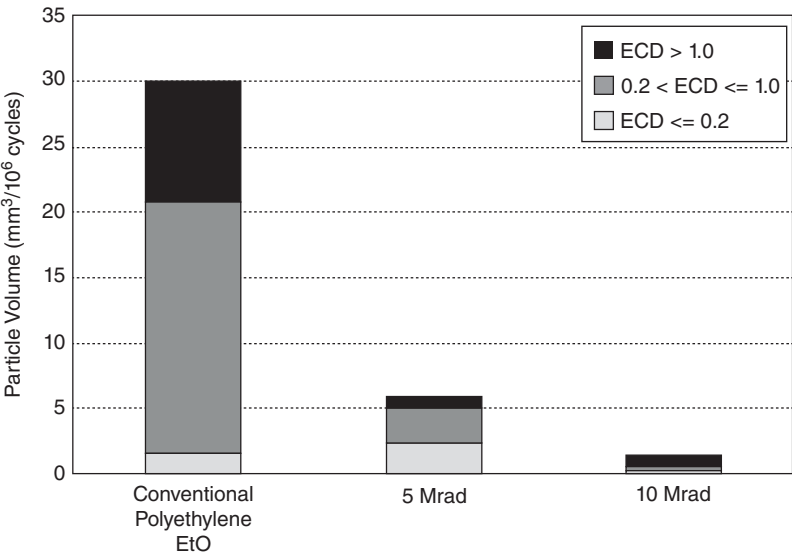


Fig. 2.17 Comparative volumes of acetabular particle generation for different size ranges per million cycles for conventional and highly cross-linked UHMWPEs at 5 and 10 Mrads resulting from hip simulation. ECD, equivalent circular diameter (from Ries MD, Scott ML, Jani

S. Relationship between gravimetric wear and particle generation in hip simulator: conventional compared with cross-linked polyethylene. *J Bone Joint Surg Am.* 2001;83(Suppl 2, Pt 2):116–122, with permission)

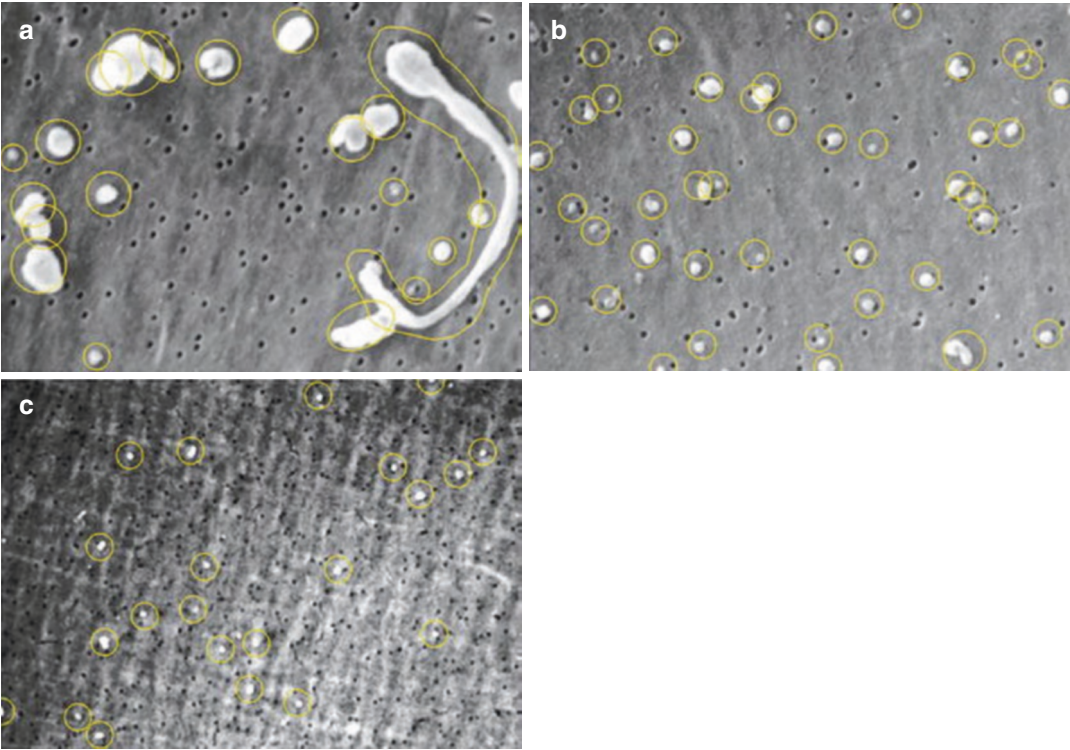
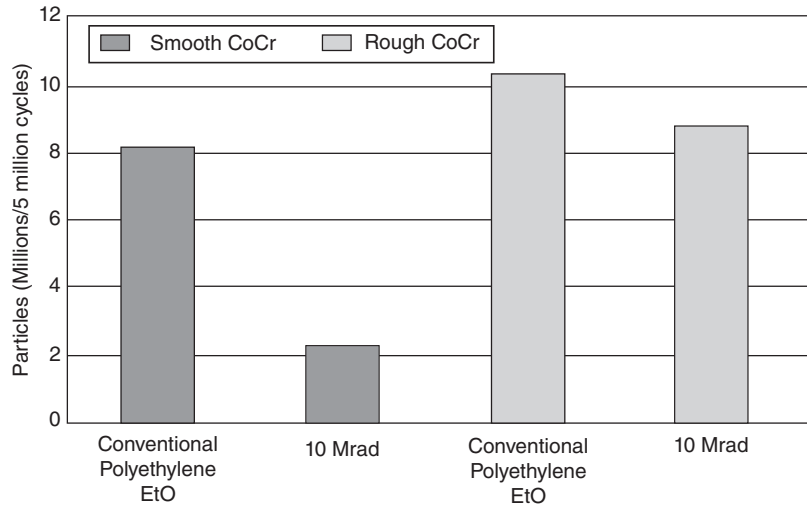


Fig. 2.18 Corresponding SEM visualization (10,000×) of particle distribution for (a) conventional and (b, c) highly cross-linked UHMWPEs at 5 and 10 Mrads, respectively, employing a 0.05-μm filter. The particles are highlighted for appreciation (from Ries MD, Scott ML,

Jani S. Relationship between gravimetric wear and particle generation in hip simulator: conventional compared with cross-linked polyethylene. *J Bone Joint Surg Am.* 2001;83(Suppl 2, Pt 2):116–122, with permission)

Fig. 2.19 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 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, with permission)



scratched surface articulation was bioreactive when placed in a culture medium and appeared to be volume-dependent [161].

The influence of surface roughness was further investigated by Scott et al. in a hip simulator comparison between conventional, EtO, and 10 Mrad UHMWPE components [162]. As one appreciates from Fig. 2.19, roughened surfaces have a negative influence on particle production where highly cross-linked UHMWPEs are employed. This was challenged by Muratoglu et al. in a study in which retrieved femoral components were articulated in knee simulation against a highly cross-linked UHMWPE [163]. Further, retrieved oxidized zirconium femoral components have demonstrated decreased surface roughness with time in-vivo, suggesting another benefit of this cobalt-chromium alternative for improving the long-term viability of knee articulations [164–167].

index and device failure following arthroplasty [171–176]. Surgical preference, however, weighs in favor of the lightweight patient as the ideal arthroplasty candidate [177]. It is also known from both physical laboratory testing and finite element analysis that load magnitude in combination with displacement are factors influencing UHMWPE damage [178–185]. 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 [186].

With the patient population pursuing total knee arthroplasty getting younger and living longer, it is imperative that contemporary implant bearing materials address these increasing demands [187]. Clinical studies are now focusing more on patient-reported outcomes and relating them to comorbidities in an effort to align expectations for both the patient and the surgeon [188–190].

An Orthopedic Triad: The Patient

Overenthusiastic patient use following total knee arthroplasty has been cited as a factor influencing failure [168–170]. 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

An Orthopedic Triad: The Surgery

The forces and torques that occur during walking gait, particularly during toe-off, promote articulation in the posteromedial quadrant of tibial inserts [191–195]. Retrieved components of failed knee arthroplasties demonstrate UHMWPE

damage patterns in this area [196–200] (Fig. 2.20). 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 [196–200]. In addition, the dynamic effects of lift-off and subsequent impact loading and unusual patient kinematics further increase the potential for posteromedial failures [201]. The influence of surgical malrotation may be appreciated in Fig. 2.21a, b, which demonstrate dramatic changes in location, contact area, and peak stresses for a PCL preserving knee in a laboratory investigation [202].

The continual emphasis on templating and the technological advances in computer-assisted and robotic navigation systems, intraoperative sensors as well as patient-specific instrumentation offer the promise that component malalignment may ultimately be minimized and patient satisfaction increased [203–209]. Eliminating the out-

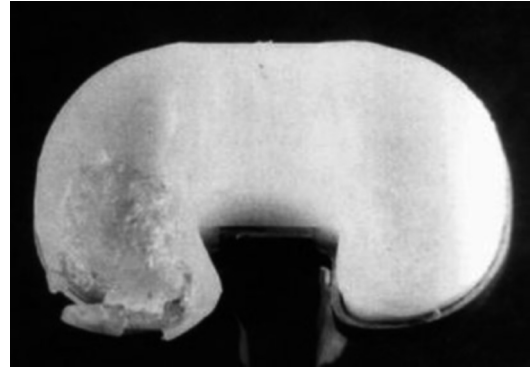


Fig. 2.20 UHMWPE tibial component retrieval showing deformation and wear in the posteromedial portion of the insert (from Swamy MR, Scott RD. Posterior polyethylene wear in posterior cruciate ligament-retaining total knee arthroplasty: a case study. *J Arthroplasty*. 1993;8:439–846, with permission)

liers in component placement will contribute to diminishing UHMWPE material damage in knee arthroplasty, however, the best technology to utilize in the achievement of this goal, is yet to be defined [210–212].

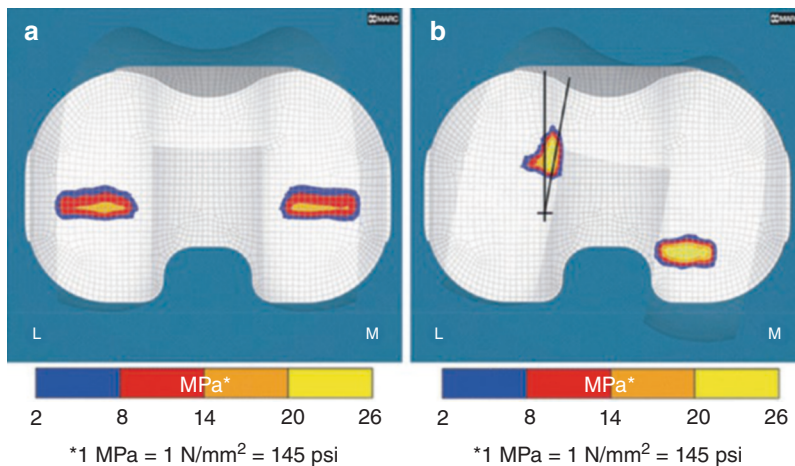


Fig. 2.21 The distribution of contact stresses at the toe-off position of walking gait for a left knee, PCL preserving design at (a) neutral rotation and (b) after the application of a 16 N-m external torque, simulating deliberate component malalignment. A dramatic increase in

peak contact stresses is observed, which is contributory to component damage (from Morra EA, Postak PD, Plaxton NA, et al. The effects of external torque on polyethylene tibial insert damage patterns. *Clin Orthop Relat Res*. 2003;410:90–100, with permission)

The Enduring Promise

The previous remarks have attempted to define problems, solutions, and unknown performance factors of bearing materials currently utilized in total knee arthroplasty as they relate to the implant, the patient, and the surgery. What is important for the reader to appreciate is that this is a continually evolving experience, which will find advocacy or limitations, with the passage of in-vivo time.

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