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Highly Crosslinked Polyethylene is Safe for Use in Total Knee Arthroplasty

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Abstract Highly cross-linked polyethylene (XLPE) has been used with good initial success in hip arthroplasty to reduce wear. However, the process of crosslinking reduces fracture toughness, raising concerns as to whether it can be safely used in total knee arthroplasty (TKA). We therefore asked whether XLPE can be used safely in TKA. We performed a retrospective review of 100 subjects receiving XLPE and compared them to 100 subjects who received standard polyethylene in the setting of TKA. The standard polyethylene group had a mean age of 70 with a minimum follow up of 82 months. The highly cross-linked polyethylene group had a mean age of 67 and a minimum follow up of 69 months (mean, 75 months; range, 69–82 months). On radiographic review, the standard group demonstrated 20 TKAs with radiolucencies; 4 of these had evidence of a loose tibial component. The standard group required three revisions related to loose tibial components. The XLPE group had 2 subjects that demonstrated radiolucencies on radiograph and no subjects with evidence of tibial loosening. There were no reoperations related to osteolysis. The data suggest XLPE in TKA can be used safely at least short- to midterm. Our study provides an impetus for further long-term investigation.
Level of Evidence: Level III, therapeutic study. See the Guidelines for Authors for a complete description of levels of evidence.

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Each author certifies that his or her institution has approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research. IRB approval was obtained. No consent was necessary for this retrospective review.

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Introduction

Since the introduction of ultrahigh-molecular-weight polyethylene (UHMWPE) by Sir John Charnley, it has become the bearing surface of choice in both THA and TKA. There has been an abundant amount of research focused on the properties of UHMWPE and attempts to maximize the wear characteristics of this bearing material [1, 3, 7, 8, 20, 26, 31, 37, 38, 44–46]. Unfortunately, not all have been successful. Attempts at changing the structure, constituent elements, and processing techniques have failed in the past. Despite these efforts, polyethylene wear continues to be the primary reason for long-term failure of TKA [1, 13, 24, 32–34, 42]. The clinical wear complications remain a consequence of complex biomechanical and biologic interactions that are dependent on the volume of wear debris, the size and shape of the debris, the resulting biologic activity, and individual patient-specific reactions [13–15, 21–23, 25, 44]. Another major factor in polyethylene wear is age [19]. It is well known that younger, more active patients can have early-onset osteolysis and extreme polyethylene wear (Fig. 1).

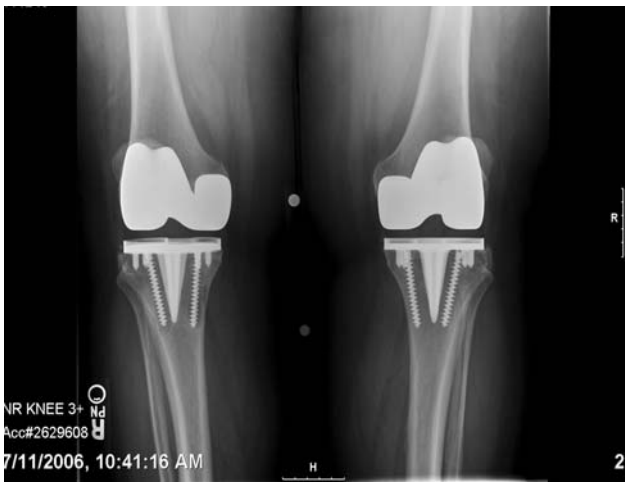

Fig. 1 Demonstrated in the figure is the AP radiograph of a patient with osteolysis. The right knee underwent TKA 5.5 years ago with conventional polyethylene. The left knee underwent TKA 5 years ago with highly crosslinked polyethylene. This figure shows a radiographic difference in the amount of lysis between the two knees.

The differences in the wear mechanisms and the particle debris created between THA and TKA have been well documented [22, 26, 41]. The biomechanical profile of the TKA articulation, including rolling, sliding, and rotation, leads to more fatigue failure, pitting, and delamination than that seen in highly congruent THA articulation. In addition, there remains the issue of backside wear of modular tibial knee inserts [9, 11, 12, 35, 36]. The issue of delamination can be a major clinical complication because this may lead to altered geometry, which can adversely affect load distribution of the implant [3]. This may lead to eventual implant failure in the form of implant fracture or disengagement. Particulate debris is mainly the result of adhesive and abrasive wear of the polyethylene that contributes to the clinical manifestation of osteolysis [22].

Particle-induced osteolysis is caused by the creation of the UHMWPE particulate debris. The cellular response, including release of proinflammatory cytokines, results in the stimulation of osteoclasts and suppression of osteoblasts. The smallest particles induce the largest response secondary to the phagocytosis by macrophages [13, 14, 21, 22]. In the face of major osteolysis, considerable bone loss may occur. The bony defects created can make revision surgery especially cumbersome [40]. The goal of improving our polyethylene bearing surfaces has been to improve the durability of the insert, decrease the number of particles, and therefore reduce the incidence of particle-induced osteolysis.

Gamma radiation sterilization causes crosslinking of polymer changes in polyethylene. This crosslinking has shown great promise in improving the wear profile of polyethylene. This has been demonstrated in the THA literature [6, 10, 26, 27]. In the presence of oxygen, gamma radiation also induces the formation of free radicals, which when combined with oxygen may cause oxidative degradation of polyethylene with age [4, 7, 8, 15, 20, 45, 46]. Because of this issue, manufacturers now use ethylene oxide gas or gamma irradiation in an oxygen-free environment as their method of sterilization. Heating the polyethylene near or above melting temperature in an oxygen-free environment after sterilization improves adhesive wear and oxidative stability. However, thermal stabilization also reduces the crystallinity of the material. This can reduce mechanical properties of the material, including strength and fatigue resistance. Several authors have previously documented these changes and believe this reduced fracture toughness should cause trepidation in choosing highly crosslinked polyethylene in TKA [5, 33, 37, 39].

Crosslinking and thermal stabilization of polyethylene improves wear characteristics of acetabular components in hip simulator studies [27] as well as in vivo radiostereometric analysis [10]. These findings have prompted investigation as to whether crosslinking would be beneficial in TKA. Recent laboratory studies suggest wear reduction rates of 94% and 43% when comparing standard and highly crosslinked polyethylene in TKA simulations [25, 28–31]. Given this new information, there is the possibility that the wear characteristics, including resistance to delamination, would be positively affected by the use of highly crosslinked polyethylene in TKA. Reduction of free radicals could also lead to reduced oxidation, decreasing the incidence of any associated fatigue failure. The investigators considered the clinical research from THA studies combined with the in vitro wear studies warranted further consideration of using highly crosslinked polyethylene in TKA [28–31].

We therefore compared the clinical and radiographic outcomes of two patient groups receiving TKA using a highly crosslinked versus a conventional polyethylene liner.

Materials and Methods

We retrospectively reviewed the clinical and radiographic outcomes of 200 consecutive total knee arthroplasties. A highly crosslinked polyethylene tibial insert, Durasul, for the Natural Knee system (Zimmer, Warsaw, IN) became available for use in February 2001. Since that time, it has been used consecutively by the senior author (AAH). We compared the first 100 cases receiving the highly crosslinked polyethylene insert with the 100 cases immediately before this date who received a conventional polyethylene insert sterilized by gamma irradiation in nitrogen (Fig. 2). Patients were evaluated with a standard physical examination, and a three-view radiographic series.

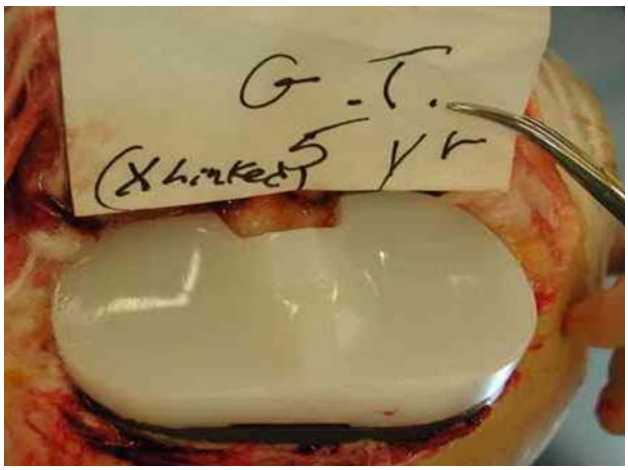

Fig. 2 Figure 2 is an intraoperative photograph of highly crosslinked polyethylene at 5 years showing no observable wear. The reason for revision was ligamentous laxity.

The conventional group consisted of 100 patients (40 male, 60 female) with an average age of 70 years (range, 41–92 years). The diagnosis was osteoarthritis in 89 patients, inflammatory arthritis in six patients, and posttraumatic arthritis in five patients. Thirty-four of the patients received a cemented TKA, whereas 66 received a noncemented technique. Thirty-one cases were performed using a PCL-preserving technique and in 69 cases, the PCL was sacrificed. In the standard group, there were 9 bilateral procedures. Six subjects received bilateral TKA in a sequential fashion under one anesthetic while 3 subjects had their bilateral TKA in a staged manner. Fourteen patients died. These records were queried at the time of their most recent follow up before their death. There were no radiographic findings demonstrating lucencies or lysis. These 14 patients were included in the survivorship analysis. In addition, seventeen patients were lost to followup, leaving 83 patients. The minimum followup from time of surgery was 82 months (mean, 91 months; range, 82–101 months).

The highly crosslinked group consisted of 100 patients (42 male, 58 female) with an average age of 67 years (range, 37–98 years). The diagnosis was osteoarthritis in 87 patients, inflammatory arthritis in five patients, and posttraumatic arthritis in eight patients. Thirty of the patients received a cemented TKA, whereas 70 received a noncemented technique. Twenty-six cases were performed using a PCL-preserving technique and in 74 cases, the PCL was sacrificed. In the highly crosslinked group, there were 5 bilateral procedures. Two received bilateral TKA in a sequential fashion under the same anesthetic while 3 had their bilateral TKA in a staged manner. Ten patients died. Eighteen patients were lost to followup, leaving 82 patients for review. The minimum followup from time of surgery was 69 months (mean, 75 months; range, 69–82 months) (Table 1).

Table 1. Demographic comparisons of the two groups

Variable	Standard polyethylene [n = 100]	Highly crosslinked polyethylene [n = 100]	p value
Male, n	40	42	0.77
Female	60	58	
Age, mean ± SD (range)	70 ± 12 (41–92)	67 ± 12 (37–98)	0.08
Diagnosis, n			0.67
OA	89	87	
Inflammatory	6	5	
Posttraumatic	5	8	
Deceased, n	14	10	0.38
Lost to followup, n	17	18	0.85
Cemented, n	34	30	0.54
Cementless	66	70	
Resurfaced patella, n	65	62	0.66
Unresurfaced patella	35	38	
PCL retaining, n	31	26	0.43
PCL sacrificing	69	74	

The sample size of n = 100 in each group provided 80% power to detect a cumulative survival probability of 99% versus 89%, representing a 10% absolute difference in revisions, using a log-rank test with an assumed 10% losses to followup. The study had only 48% power to detect a 5% absolute difference in revisions.

All surgeries were performed by the senior author using the Natural Knee II system (Zimmer). The tibial components are modular. The base plate is an asymmetric design made of titanium alloy. The locking mechanism was snap-fit. Posterior cruciate ligament (PCL) retaining and sacrificing techniques were both used based on the amount of degeneration present in the ligament and if there was a major preoperative deformity. If the PCL was sacrificed, we used an ultracongruent polyethylene insert to provide anteroposterior stability [16–19]. The decision to use a cemented versus press-fit technique was based on the age of the patient and the quality of bone. Those patients receiving the press-fit technique had bone slurry placed at the bone-component interface before application [16]. All press-fit tibial components were augmented with two titanium cancellous screws. We based the decision to resurface the patella on patient age and the condition of the articular cartilage intraoperatively. We performed patelloplasty, including synovectomy and removal of osteophytes, in the nonresurfaced cases. A standard postoperative protocol was used in all patients, which includes 6 weeks of weight bearing with an assistive device [16–19]. All patients were instructed to avoid impact activities postoperatively.

The conventional group received compression-molded polyethylene, which was gamma-irradiated in nitrogen. The highly crosslinked group received compression-molded polyethylene sterilized with ethylene oxide gas preheated at 125°C and irradiated with a dose 9.5 Mrad (95 kGy) through an electron beam. The postirradiation thermal treatment consisted of melting at 150°C [28–31].

Preoperatively, a standard history and physical examination was performed including range of motion. Preoperative and intraoperative data collected from the charts included diagnosis, cement technique, whether or not the patella was resurfaced, and whether or not there were any complications or revisions. The Social Security Administration data bank was used to determine the date of death.

Standard AP, lateral, and sunrise views were evaluated for the presence of osteolysis, lucency, and any evidence of loosening or wear. The radiographs were evaluated by a principal investigator (JTH). The exact dimensions of lysis or lucency were not calculated because we did not employ computed tomography in this retrospective study. Therefore, in order to increase the specificity of this study, any evidence of lysis seen on both the AP and lateral radiograph were included and thought to have polyethylene induced osteolysis.

We compared continuous variables between the two groups using t tests and categorical variables with chi-square tests. Time to revision for wear, which was the primary outcome, was analyzed using a log-rank test with survival probabilities displayed using a Kaplan-Meier plot. As no revisions occurred in one of the groups, the log-rank test degenerated to a p value of 1.00, and so a Fisher's exact test was applied as well. Given that only 3 events occurred, a Cox regression model could not be used to control for potential confounding variables. Doing so would produce overfitting, where unreliable associations would arise from using too many predictor variables for the number of events. All statistical tests were for a two-sided comparison with significance set at $p < 0.05$. Statistics were computed using Stata 10 software (StataCorp, College Station, TX, USA).

Results

In the highly crosslinked group, we observed two tibial radiolucencies on radiographs in two patients with no signs of loosening or eccentric wear of the polyethylene. Five patients underwent reoperation, one for open reduction and internal fixation of a periprosthetic femur fracture, one for infection, one for laxity (Fig. 3), one for a loose body, and one had an open synovectomy for arthrofibrosis. Preoperative range of motion averaged 1° to 113° (extension, 0°–15°; flexion, 30°–135°). The average postoperative range of motion was 1° to 115° (extension, 0°–20°; flexion, 70°–130°).

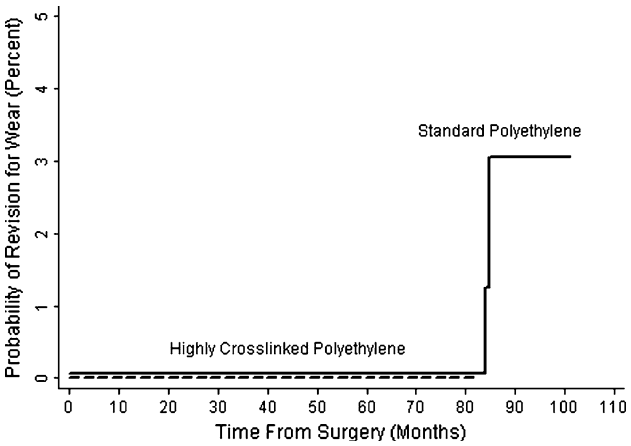

Fig. 3 Demonstrated are the Kaplan-Meier failure probabilities for revision for loose tibial component. There was not a significant difference in revisions between the groups (highly crosslinked: 0 revisions; standard polyethylene: 3 revisions, log-rank test, p = 1.00).

In the standard polyethylene group, we found 20 radiolucencies on radiographs in 20 patients (Fig. 1). There was radiographic evidence of polyethylene wear noted in four patients and evidence of tibial loosening in four patients. Nine patients underwent reoperation, three had revision TKA for a loose tibial component, two for treatment of infection, two for instability, one for patellar revision, and one for an arterial popliteal thrombus treated with revascularization. One patient with a loose tibia was excluded from the study. The patient was part of a manufacturers' recall of components and was therefore not included in the outcomes analysis. Preoperative range of motion averaged 1° to 112° (extension, 0°–30°; flexion, 50°–150°). The average postoperative range of motion was 0° to 109° (extension, 0°–5°; flexion, 35°–135°).

We observed no difference (log-rank test, p = 1.00; Fisher's exact test, p = 0.25) in revisions for a loose tibial component between the groups (no revisions for the highly crosslinked group versus three revisions in the standard polyethylene group) (Fig. 3). Two of the revisions occurred at 84 months and one at 86 months.

There were no cases of early catastrophic failure related to polyethylene in either the highly crosslinked or standard polyethylene groups.

Discussion

Highly crosslinked polyethylene first became available in February 2001. Although it has become clear that there is markedly decreased wear with its use in THA [6, 10, 26, 27], there is debate regarding its use in TKA despite promising in vitro studies [23, 28–31, 37], primarily owing

to a reduction in fracture toughness. The intended purpose of the present study was to provide a clinical in vivo analysis of highly crosslinked polyethylene when used in TKA.

Limitations of this study must be identified and considered when interpreting the presented data. A large percentage of patients were lost to followup during this study. An attempt was made to contact these patients. The senior author's practice represents a tertiary referral center. Many patients live greater than 200 miles from the institution and were unwilling to commute. Ours was not a retrieval analysis and, therefore, we could not inspect the devices for pitting or delamination. Instead, we used radiographs to assess degree of osteolysis and/or the development of progressive compartment asymmetry in the joint space [2]. There are data [43] suggesting particles generated by the highly crosslinked polyethylene are smaller when compared with traditional UHMWPE. These smaller particles are more biologically active and theoretically could create more osteolysis [11, 14, 21, 22, 33, 43]. Patients can show signs of osteolysis while being asymptomatic and the rate of progression of osteolysis is variable. Nonetheless, the development of osteolysis indicates wear. Although considerable wear must be present along with sufficient time to create the osteolysis and so radiographs only indicate wear late in the process. Thus we believe radiographs are appropriate to assess osteolysis and extrapolate the findings to wear. Another limitation of our study comes from the understanding that generation of polyethylene wear and subsequent development of osteolysis are multifactorial. Patient factors, implant variability, and surgical technique all play important roles in the development of polyethylene wear and subsequent osteolysis [13–15, 18, 21–23, 25, 44]. Perhaps the most important factor in wear is related to patient activity, and this is clearly the most difficult variable to control. All patients in the current study were given instructions regarding activity modification and all patients underwent the same postoperative activity protocol. The degree of compliance with this was not assessed. To account for implant variability and surgical technique, all patients received the Zimmer Natural Knee System, and all patients had their surgery performed by one surgeon.

When trying to compare the data presented in this study with existing literature, it is difficult because no in vivo analysis has been conducted using highly crosslinked polyethylene in TKA. In knee arthroplasty, in which there is less contact area and, thus, increased contact stresses, there is concern for its use given the mechanical properties of highly crosslinked polyethylene [37]. We point to the need for material improvement to decrease the future revision burden as well as to the in vitro data to justify the current vivo study [42].

In vitro analysis has been promising. Muratoglu et al. [28] performed knee simulator testing on both highly crosslinked polyethylene and conventional polyethylene to compare the two with regard to wear. The highly crosslinked polyethylene tibial inserts showed no delaminations even after aggressive aging in vitro. There was also a dramatic reduction in adhesive and abrasive wear when compared with conventional polyethylene with knee simulation [28–31].

Although Wright [47] agrees adding crosslinking to polyethylene is beneficial in eliminating wear rates, delamination, and pitting as demonstrated by knee simulator studies, he states that the particles may be more biologically active because they are smaller. Wright stated the mechanical changes that take place with crosslinking polyethylene result in reduced fracture toughness and resistance to fatigue-crack propagation compared with conventional UHMWPE causes concern at the locking mechanism or with components of constraint made by polyethylene [5, 47].

These concerns are shared by Ries [37]. His study expresses concern that although highly crosslinked polyethylene clearly reduces wear, the changes in the mechanical properties cannot be ignored. Ries believes the use of this material in TKA may contribute to mechanical failure [37]. This concern was reiterated in 2005 by Ries and Pruitt [39]. In theory, using highly crosslinked polyethylene in a less conforming joint such as TKA, contact stresses are high and fatigue wear mechanisms occur more typically. Although resistance to crack initiation is higher, resistance to crack propagation is lower; therefore, Ries concludes it should not be used in TKA [37].

This argument is challenged by Jasty et al. [23] in which they maintain fatigue strength of the material is more important than static mechanical strength for performance in vivo. Because extensive device fatigue tests have also confirmed total joints with highly crosslinked polyethylene performed 20 years of simulated clinical use without any evidence of failure, Jasty et al. believe examining the clinical use of this material in TKA is justified [23].

When synthesizing the data presented in this study with previous reports in the literature, the use of highly crosslinked polyethylene in TKA should be considered a viable option. The data suggest highly cross-linked polyethylene when used in the setting of TKA is as safe as standard polyethylene at early to mid-term follow up and provide an impetus for further longer-term investigation.

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