How Does Wear Rate Compare in Well-functioning Total Hip and Knee Replacements? A Postmortem Polyethylene Liner Study

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Abstract

Background The longevity of total hip (THR) and knee replacements (TKR) that used historical bearing materials of gamma-in-air sterilized UHMWPE was affected more by osteolysis in THRs than in TKRs, although osteolysis remains a concern in TKRs. Therefore, the study of polyethylene wear is still of interest for the knee, particularly because few studies have investigated volumetric material loss in tibial knee inserts. For this study, a unique collection of autopsy-retrieved TKR and THR components that were well-functioning at the time of retrieval was used to compare volumetric wear differences between hip and knee polyethylene components made from identical material.

Questions/purposes The following questions were addressed: (1) How much did the hip liners wear and what

wear patterns did they exhibit? (2) How much did the knee inserts wear and what wear patterns did they exhibit? (3) What is the ratio between TKR and THR wear after controlling for implantation time and patient age?

Methods We compared 23 THR components (Harris-Galante [HG] and HG II) and 20 TKR components (Miller-Galante [MG II]) that were retrieved postmortem. The components were made from the same polyethylene formulation and with similar manufacturing and sterilization (gamma-in-air) processes. Twenty-one patients (12 males, nine females) had THRs and 16 (four males, 12 females) had TKRs. Patients who had TKRs had an older ($p = 0.001$) average age than patients who had THRs (age, 75 years; SD, 10, versus 66 years; SD, 12, respectively). Only well-functioning components were included in this study. Therefore, implants retrieved postmortem from physically active patients and implanted for at least 2 years were considered. In addition, only normally wearing TKR components were considered, ie, those with fatigue wear (delamination) were excluded. The wear volume of each component was measured using metrology. For the tibial inserts an autonomous mathematic reconstruction method was used for quantification.

Results The acetabular liners of the THR group had a wear rate of 38 mm^3 per year (95% CI, 29–47 mm^3/year). Excluding patients with low-activity, the wear rate was 47 mm^3 per year (95% CI, 37–56 mm^3/year). The wear rate of normally wearing tibial inserts was 17 mm^3 per year (95% CI, –6 to 40 mm^3/year). After controlling for the relevant confounding variable of age, we found a TKR/THR wear rate ratio of 0.5 (95% CI, 0.29–0.77) at 70 years of age with a slightly increasing difference with increasing age.

Conclusions Excluding delamination, TKRs exhibited lower articular wear rates than THRs for historical polyethylene in these two unique cohorts of postmortem retrievals.

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Clinical Relevance The lower TKR wear rate is in line with the lower incidence of osteolysis in TKRs compared with THRs.

Introduction

During the next 5 years, revision total knee replacements (TKR) are projected to increase by 30%; nearly twice as fast as revision total hip replacements (THR) [22]. Although infection and instability are dominant reasons for early failure, aseptic loosening accompanied by periprosthetic osteolysis becomes the primary revision cause of TKR after 5 years in situ [11]. Wear debris from UHMWPE has been identified as a major contributor to the occurrence of periprosthetic osteolysis. Jacobs et al. [16] reported that along with particle size and shape, wear volume is a major determinant of osteolytic potential. Although PE wear previously was a larger problem, the introduction of highly crosslinked PE for acetabular liners for the hip has mostly solved this problem.

Historically, wear in TKRs has been evaluated by classifying wear patterns on retrieved PE inserts [14]. Therefore, there is little quantitative wear information for TKR inserts worn in vivo. This is different for the hip, where the conforming ball-and-socket joint allows for quantitative wear measurements from planar radiographs. However, the precision of these measurements is insufficient to produce meaningful wear data for nonconforming TKR inserts [3, 4, 36]. Some investigators therefore resorted to linear wear estimates based on caliper or dial indicator thickness measurements of retrieved tibial inserts [4]. Others have worked on more complex technologies to allow quantitative, volumetric wear measurements on PE inserts [9, 19, 35, 36]. Because the incidence and extent of osteolysis after TKRs are less than that after THRs [12], we hypothesized that, for the same interval and in the absence of material fatigue (PE delamination), the TKR/THR wear volume ratio would be less than one.

The analysis of retrieved PE inserts after revision or removal surgery is not without problems. Most of the available material was retrieved for a reason, which may mean that wear patterns and volume do not represent well-functioning components. We therefore limited the analysis to inserts and liners obtained at autopsy from patients in our clinic who had regular followups. Furthermore, to minimize confounding material factors, we limited the inclusion to components manufactured from the same PE powder with the same processing and sterilization history. Specifically, we addressed the following research questions: (1) How much did the hip liners wear and what wear patterns did they exhibit? (2) How much did the knee inserts wear and what wear patterns did they exhibit? (3)

What is the ratio between TKR and THR wear after controlling for implantation time and patient age?

Materials and Methods

Study Design

To effect as direct a comparison as possible between the THR and TKR groups for wear, the acetabular cup liners and tibial inserts chosen for this study were produced by the same manufacturer during the same period, from the same type of PE (same resin and consolidation technique), using a similar machining protocol and sterilization process, and implanted at the same medical center. Implants retrieved postmortem from physically active patients and implanted for at least 2 years were considered to represent well-functioning prostheses. The respective Harris hip scores and Hospital for Special Surgery scores were not available for all subjects. Therefore, judgment regarding the activity level was made based on medical records and interviews with the responsible clinical nurses. Patients unable to walk short distances without a walking aid were considered not physically active. One patient was known to have been completely bed bound for the last 1.5 years before dying. It was not feasible to match the groups for sex, age at implantation, and implantation duration. Wear of the articulating surfaces of the acetabular liners and the tibial inserts was determined by metrology. Wear patterns and backside wear were evaluated by visual examination and optical microscopy.

Retrievals

Initially, 23 THR and 21 TKR components that were retrieved between 1992 and 2004 were screened for possible inclusion in the study. One TKR component was excluded because it was in situ less than 2 years. Another TKR and five THR components were excluded because they were from patients considered to have low activity. Four TKR components, including those from the patient who had low activity, were excluded post hoc owing to severe delamination. The acetabular liners and tibial inserts of these joint replacements were made from ram-extruded GUR 4150 (Ticona, [now Celanese Corporation], Irving, TX, USA), machined, and gamma-sterilized in air with a nominal dose of 25 kGy. All implants were manufactured by Zimmer Inc (Warsaw, IN, USA). The THR group included two different designs: the Harris-Galante (HG I) and its successor, the HG II. Differences between these two designs were limited to the locking mechanisms between the acetabular shell and liner and features of the shell [10].

Table 1. Overview of patient and retrieval information

Procedure	Design [§]	Number of patients	Number of retrievals	Number of patients with bilateral procedures	Mean age of patients (years)	Sex (F, M)	Side (L, R)	Mean implantation time (years)	Mean shelf time (months)
THR	HG, HG II	21	23	2	66 (SD, 12)	9, 12	11, 12	10 (SD, 3.5)	7 (SD, 6)
TKR	MG II	16	20	4	75 (SD, 10)	12, 4	11, 9	7 (SD, 3)	5 (SD, 5)
p value		0.52	0.31		0.001	0.08	0.76	0.007	0.114
THR [*]	HG, HG II	16	18	2	64 (SD, 12)	7, 9	7, 11	10 (SD, 3.5)	7 (SD, 6)
TKR [†]	MG II	12	13	1	76 (SD, 10)	10, 2	6, 7	6 (SD, 2)	4 (SD, 4)
p value		0.45	0.37		0.012	0.03	0.68	0.002	0.012

* Excluding patients with low activity; [†]excluding patients with low activity and delaminated components; [§]all manufactured by Zimmer Inc (Warsaw, IN, USA); THR = total hip replacement; TKR = total knee replacement; HG = Harris-Galante; MG = Miller-Galante.

The cup liners articulated against CoCrMo femoral heads, of which 21 were 28 mm and two were 32 mm in diameter. The femoral stem was cemented in 10 of 23 cases, and the acetabular shell was uncemented in all cases. The tibial liners were of the Miller-Galante II (MG II) design and articulated against a CoCrMo femoral component. All the TKR components were cemented.

All subjects in the study were part of an institutional review board-approved postmortem retrieval program at Rush University Medical Center [15]. After removal, all hip and knee specimens were placed in 10% neutral buffered formalin immediately on arrival to the laboratory. After fixation, further dissection of the periprosthetic tissues and disarticulation of the PE articulation surfaces were performed.

There were 21 (12 males, nine females) patients with THRs and 16 (four males, 12 females) patients with TKRs, yielding 23 cup liners and 20 tibial inserts. The THR group included two patients with bilateral THRs and the TKR group included four patients with bilateral TKRs. Bilateral hips and knees were included because of the already low number of components available. We assumed that inclusion of patients with bilateral procedures would not markedly bias the data because they constitute a minority, and studies suggest a low correlation between sides for hip liner wear in patients with bilateral procedures [17, 28]. Plots of residuals versus patients showed no patterns indicative of independence violation. In comparing the TKR and THR groups, 23 liners and 20 inserts permitted detection of an effect size (difference of means divided by the SD) of 0.88 with a power level of 0.8 at a 95% confidence level for a two-tailed t-test univariate comparison. Given an estimated SD of 15 mm³ per year for the wear rates, this effect size corresponds to detecting a difference of 13 mm³ per year between wear rates, which, given an overall average wear rate of approximately 35 mm³ per year, corresponds to detecting a ratio of the low mean to the high mean wear rate of approximately 0.68 or less. The

TKR group had a greater proportion of females and patients who were older at the time of implantation, and they had a longer implantation time than patients in the THR group. For historical PE, shelf time had marked influence on the degree of oxidation [6], which also could affect the wear behavior [27]. However, the component shelf times were comparable for both types of implants (Table 1).

Surgery was performed by six different surgeons (JOG, JJJ, AGR, SG, MBS, RP) at Rush University Medical Center. Four surgeons performed THRs and TKRs (JOG, JJJ, AGR, SG), one performed only THRs (MBS), and one only TKRs (RP). All components were well fixed at the time of postmortem retrieval.

Wear Assessment

The occurrence of different wear patterns was investigated by visual inspection with a magnifying glass and white light stereomicroscopy (Stemi^{TM} 2000-C; Zeiss, Oberkochen, Germany). Wear patterns were classified as polishing, scratching, striations, pitting, and delamination [39]. Backside wear also was evaluated by stereomicroscopy. The presence of manufacturer's machining marks on the acetabular liner backside and the initial, as-manufactured morphologic features of the surface of the tibial inserts were indicators that there was minimal backside wear. The wear volume of the acetabular liners and the tibial inserts was measured using a coordinate measuring machine (SmartScope®; Optical Gaging Products, Rochester, NY, USA).

Acetabular liner wear was determined as previously reported [29, 37]. The metrology measurements were conducted using a touch probe with a 3-mm ruby ball (TP20; Renishaw, Wotton-under-Edge, UK). Data points were collected in 45 scans across the dome with a density of 150 per scan. In addition, 2000 data points were

Fig. 1A–B Examples of wear penetration maps of postmortem retrieved (A) acetabular and (B) tibial liners are shown.

collected on each liner in a ring close to the rim spanning 0° to 20° latitude. The obtained 8750 data points per liner were processed to yield a penetration map (Fig. 1A) and the estimated total volume loss at the articular surface of each cup liner. Similar protocols have been used by other investigators [13, 24, 30]. The linear wear rate (mm/year) was determined as the maximum penetration divided by time in situ.

For the tibial inserts, the liner surface was scanned with a low-incidence laser in place of a touch probe at a nominal $100 \times 100 \mu\text{m}$ in-plane resolution with a depth accuracy of $2 \mu\text{m}$, resulting in approximately 400,000 data points of the surface. The higher amount of data points compared with the acetabular liner was necessary because of the more complex surface geometry of the tibial liner. Using a previously described and validated method known as autonomous reconstruction [19], a design-congruent parametric surface was manually registered to unworn surface regions with custom MATLAB® software (MathWorks Inc, Natick, MA, USA) guided by visual assessment. Next, surface parameters were optimized using a least-squares minimization on points within $\pm 50 \mu\text{m}$ of the virtual surface. By calculating the volume

difference between the virtual and the measured surface, the spatial distribution of volume loss was determined as the total volume loss. The validation of this technique included mass removal and wear simulator experiments [19]. In both cases, the estimated volume loss by autonomous reconstruction was compared with measured mass loss producing a linear regression slope of one with high coefficients of determination ($R^2 > 0.95$). As in the validation study, the medial and lateral compartments of each insert were analyzed separately, and the linear penetration at each data point was plotted as a map of volume loss on the insert (Fig. 1B). The linear wear rate (mm/year) was determined as the average of the maximum penetration divided by time in situ of the medial and lateral condyles.

Global volumetric wear rates (mm^3/year) for the THR liners and TKR inserts were calculated as the linear regression slope of the measured volume loss versus time in situ. Individual component wear rates then were calculated after adjusting the measured liner or insert volume loss for the volume loss resulting from creep during the bedding-in process estimated from a positive intercept of the regression line [1, 27]. Individual wear rates were calculated for modeling purposes and because their variance is less sensitive to the range of in situ times than the variance of the regression slope. A regression model for the individual wear rates as a function of age was generated for the liner group and for the insert group to adjust for the effect of patient age when comparing the wear rates of the two groups. The THR model also included sex as a factor, but not the TKR model because there were too few males ($n = 2$). The regression analyses were performed with IBM SPSS Statistics for Windows, Version 19.0 (IBM Corp, Armonk, NY, USA) or Design-Expert® 9 (Stat-Ease, Inc, Minneapolis, MN, USA). A patient age of 70 years was chosen because it was in the age range for the THR and TKR groups. Data normality was checked with Q-Q or normality plots. A probability level of 0.05 or less was chosen for reference, but not as a binary accept-reject criterion.

Results

On the THR acetabular liners, the predominant wear feature was polishing along with fine scratches. In two cases there were a few isolated pits, perhaps caused by bone cement particles. The global volumetric wear rate for the acetabular liners was $38 \pm 14.5 \text{ mm}^3$ per year (95% CI, 8–68 mm^3/year ; $R^2 = 0.25$; $p = 0.016$) (Fig. 2), which was comparable to the mean individual wear rate of 38 mm^3 per year adjusted for bedding-in (95% CI, 29–47 mm^3/year) (Table 2), indicating a good fit for the linear

regression model. The linear wear rate was 0.093 mm per year (95% CI, 0.075–0.12 mm/year). Excluding patients with low activity, the THR liner wear rate, based on the regression line, increases to 54 mm³ per year (95% CI, 25.5–82 mm³/year) and the mean individual wear rates increase to 47 mm³ per year (95% CI, 37–56 mm³/year). The corresponding linear wear rate for this group was 0.103 mm per year (95% CI, 0.086–0.12 mm/year) (Table 2). There was no difference between HG and HG II components ($p = 0.598$) or THRs with cemented or uncemented femoral stems ($p = 0.161$). The amount of backside wear appeared minimal given that the initial machining marks were widely intact on all liners.

All the TKR tibial inserts showed a distinct wear scar on the lateral and medial sides, mainly characterized by polishing, along with scratches and striations, some elongated in the AP direction and some randomly oriented, as described in previous studies [39, 40]. Pitting occurred in all but four inserts as well, but was limited to fewer than 10 pits on each side. Seven tibial inserts showed delamination in the wear

scar area. Three were severely delaminated, one showed localized material removal, and three exhibited areas with obvious subsurface cracks (Fig. 3). The global volumetric wear rate for the TKR group was 69.5 mm³ per year (95% CI, 41–97.5 mm³/year), but the linear fit was poor (Fig. 4), mainly owing to the delaminated liners. Wear for the latter more closely followed an exponential increase with implantation time (Fig. 4), consistent with a different wear mechanism (delamination). Excluding these components, the global wear rate was 17 mm³ per year (95% CI, –6 to 40 mm³/year) (Fig. 4), which was comparable to the mean individual wear rate of 18 mm³ per year adjusted for bedding-in (95% CI, 10–25.5 mm³/year). The corresponding linear wear rate for this group was 0.109 ± 0.008 mm per year (Table 2). The backside of all the inserts still showed the imprinted serial numbers and the initial texture resulting from the manufacturing. Thus, the contribution of backside wear to the overall wear volume is expected to be minimal.

The wear rate of the THR liners was double that of the TKR inserts for the specific designs analyzed in this study, including those from only active patients, excluding delaminated TKR inserts, and correcting for patient age. For a 70-year-old patient, the THR and TKR wear rates were estimated to be 44 mm³ per year (95% CI, 34.5–57.5 mm³/year) and 22 mm³ per year (95% CI, 14–30 mm³/year), respectively, resulting in a TKR/THR ratio of 0.5 (95% CI, 0.32–0.73). The difference in wear becomes larger with increasing patient age according to the regression model (Fig. 5). The coefficients for the effect of age on wear rate were comparable for the THR and TKR groups: -0.598 mm³ per year ($p = 0.159$) and -0.709 mm³ per year ($p = 0.048$), respectively, the negative sign indicating a decrease of wear rate with age. There was no difference in wear rate between males and females in the THR group, with the numbers available ($p = 0.139$). The number of males ($n = 2$) in the TKR group was too small to analyze any association with sex.

Fig. 2 The plot shows volumetric wear with time in situ for the THR acetabular liners.

Table 2. Mean volumetric wear and linear penetration for THRs and TKRs*

Implant	Wear volume (mm ³)	Global wear rate (mm ³ /year)	Individual volumetric wear rate (mm ³ /year)	Corrected [†] individual volumetric wear rate (mm ³ /year)	Maximum linear penetration (mm)	Linear wear rate (mm/year)
THR (all)	408 (SD, 268)	38 (95% CI, 8–68)	41 (SD, 21)	38 (SD, 21)	0.9 (SD, 0.5)	0.09 (SD, 0.04)
THR (active patients)	464 (SD, 261)	55 (95% CI, 28–82)	47 (SD, 18)	47 (SD, 18)	1 (SD, 0.5)	0.1 (SD, 0.03)
TKR (all)	250 (SD, 240)	69 (95% CI, 41–98)	34 (SD, 30)	NA	0.6 (SD, 0.6)	0.09 (SD, 0.07)
TKR (nondelaminated)	143 (SD, 69)	17 (95% CI, –1 to 58)	28 (SD, 54)	18 (SD, 13)	0.4 (SD, 0.2)	0.08 (SD, 0.06)
TKR (delaminated)	447 (SD, 320)	NA	44 (SD, 27)	NA	1.2 (SD, 0.8)	0.12 (SD, 0.07)

THR = total hip replacement; TKR = total knee replacement; * the maximum linear penetration for TKRs was determined as the average value of the medial and lateral sides; [†]intercept from regression model was subtracted to adjust for creep; NA = not applicable.

Fig. 3A–B The tibial inserts in these photographs show (A) localized and (B) severe delamination.

Fig. 4 The plot shows volumetric wear with time in situ for the TKR tibial inserts. The delaminated components appear to show exponential wear.

Discussion

Longevity of THRs and TKRs in which historical PE was used often was limited by PE particle-induced osteolysis; although to a lesser degree, PE wear continues to be a concern in contemporary joint replacement designs. Interestingly, the incidence of osteolysis appears lower in patients with a TKR than a THR [12]. We hypothesized

Fig. 5 A comparison of modeled volumetric wear rates depending on patient age for the THR liners and the TKR inserts is shown.

that, for the same interval and in the absence of material fatigue, the TKR/THR wear volume ratio would be less than one. Therefore, we compared in vivo PE volumetric wear rates of postmortem retrieved THR and TKR prostheses made from the same historical PE and found approximately twice as much wear for acetabular liners compared with tibial inserts when excluding components with delamination, and when excluding patients who were known to be minimally active.

A major limitation of this study is that historical PE no longer is in clinical use. However, it was our goal to compare the extent of wear in THRs and TKRs under comparable conditions regarding material properties. Another limitation was that the TKR group had a greater proportion of females, the patients were older at the time of implantation, and they had a shorter implantation time. However, both retrieval groups had components with comparable shelf times, and a regression model was used to adjust for the effect of patient age. TKR prostheses that had additional surface fatigue, in the form of delamination in some cases, had to be addressed. The larger debris generated from delamination can be expected to have a low effect on the occurrence of osteolysis [16]. Therefore, TKR components with and without delamination had to be differentiated post hoc. In addition, it was our goal to analyze the wear of well-functioning components. Postmortem retrieved implants can be used as a well-functioning control group [15]. However, in some cases, the medical records showed that the patient was not active owing to old age or a walking impairment. Exclusion of such patients ensured that the wear rate was not underestimated.

It is logistically difficult to retrieve postmortem components [15], resulting in a relatively low number of subjects compared with numbers in studies of retrievals from revisions [2, 5, 7, 10]. Thus, there may have been

Table 3. TKR and THR wear rate comparison*

Study	Type of study	Design	Volumetric wear rate (mm ³ /year [†] or mm ³ /million cycles [‡])	Liner wear rate (mm/year)	Wear assessment
Current study	Retrieval TKR	MG II (Zimmer, Warsaw, IN, USA)	18 (SD, 13) (no delamination); 34 (SD, 30) (with delamination)	0.08 (SD, 0.06) (no delamination); 0.09 (SD, 0.07) (with delamination)	Metrology (only active patients, postmortem retrieved)
Schwenke et al. [32]	Simulator TKR	MG II	22.44 (SD, 4.5) (load control); 9.88 (SD, 0.9) (displacement control)		Gravimetric
Muratoglu et al. [27]	Simulator TKR	Natural-Knee ® II (Centerpulse, Winterthur, Switzerland)	8.5 (SD, 1.6); 8.3 (SD, 0.9)		Gravimetric, metrology
Teeter et al. [35]	Simulator TKR	Not specified (medium conformity)	23 (28 from 0–3.2 million cycles; 17 from 3.2–6.1 million cycles)		Gravimetric
Engh et al. [9]	Retrieval TKR	Anatomic Modular Knee (DePuy, Warsaw, IN, USA)		0.054 (SD, 0.083) (medial); 0.029 (SD, 0.029) (lateral)	Liner thickness measurements from retrievals
Collier et al. [3]	Retrieval TKR	Anatomic Modular Knee		0.153 (gamma-irradiated in air)	From radiographs
Engh et al. [8]	Retrieval TKR	(PFC ® Sigma ® , DePuy)	74 (SD, 49)		Micro-CT
Current study	Retrieval THR	HG I and HG II (Zimmer)	47 (SD, 18)	0.09 (SD, 0.04)	Metrology (only active patients, postmortem retrieved)
French et al. [10]	Retrieval THR	HG I and HG II		0.12 (SD, 0.08) (HG II); 0.14 (SD, 0.07) (HG I)	Liner thickness measurements from retrievals
Duffy et al. [7]	Retrieval THR	HG		0.19 (range, 0–0.88)	From radiographs (patients 50 years and younger)
Kurtz et al. [23]	Retrieval THR	HG I, Trilogy (Zimmer) and RingLoc ® , HexLoc (Biomet, Warsaw, IN, USA)		0.24 (range, 0.08–0.41)	From radiographs
Martell et al. [25]	Retrieval THR	HG	74 (SD, 51); –82 (SD, 57)	0.14 (SD, 0.09); 0.17 (SD, 0.13)	From radiographs
Sychterz et al. [34]	Retrieval THR	Several designs from same generation as HG/HG II	39.8 (range, 1.0–131.3)	0.07 (range, 0.02–0.18)	Shadow graph technique (postmortem retrieved)

*Wear rates from in vitro studies were converted from mg per million cycles to mm³ per year by assuming a constant UHMWPE density of 0.931 mg/mm³; [†] Retrieval studies; [‡] Simulator studies; THR = total knee replacement; THR = total hip replacement; MG = Miller-Galante; HG = Harris-Galante.

other factors, or confounding variables, that could not be studied by multivariate analysis owing to the small sample groups. The results of our study are valid only for the specific implant designs that were studied. We compared two similar THR designs and one TKR design. At this point it is unknown whether the observed relationship between the respective wear rates applies to other designs.

The focus of our study was articular wear. Currently, to our knowledge, there are no validated techniques to

accurately quantify backside wear, and visual examination pointed to backside wear being low for the components in this study. Thus, examination of the cups' backsides revealed that the initial machining marks were widely intact with only small areas showing damage, mainly characterized by plastic deformation attributable to screw indentation from the acetabular shell. Consistent with these observations, Krieg et al. [20] found backside wear on one specific cup liner design to be less than 3% relative to

articular wear after a median implantation time of 54 months, and finite element analysis suggested that it is at least three orders of magnitude smaller than articular wear [21]. However, backside wear on tibial inserts has been reported to be more substantial, with values of 6% to 30% relative to articular wear as determined from tests in simulators [5]. In our study, however, the manufacturer's engraving marks on the backside of the liners were still visible on all 20 components. In addition, the initial texture from the machining process was widely intact on all inserts with some also showing screw-hole indentations from the tibial tray. Based on these observations we conclude that the effect of backside wear was low. This outcome is not surprising for the tibial inserts because the MG II design exhibits low conformity and to a large extent, backside wear in TKRs is strongly associated with high-conformity tibial inserts [38].

The mean wear rate of 38 mm³ per year for the entire THR group was slightly less than the range of 40 to 83 mm³ per year previously reported for historical PE of that generation, GUR 4150 gamma-sterilized in air [25, 34]. Exclusion of patients with low activity increased the global wear rate to 47 mm³ per year, which is within this published range (Table 3). The corresponding linear wear rate of 0.11 mm per year also was in the range of 0.07 to 1.6 mm per year reported for HG and HG II components retrieved at revision (Table 3) [7, 10, 23, 25, 34]. The absence of delamination on the articulating surface can be explained by the low contact stresses produced by the highly congruent contact of THRs. Adhesive PE wear thus dominates [26], which, coupled with the multidirectional hip motion, produces polished wear surfaces.

The mean wear rate of 18 mm³ per year for the non-delaminated tibial liners falls in the range of 9 and 23 mm³ per million cycles obtained in physiologic knee simulators on the same or similar TKA designs [27, 32, 35] (Table 3), where 1 million cycles is considered to be approximately equivalent to 1 year in vivo. Other than the study by Knowlton and Wimmer [19], we are aware of only one other study reporting measured volumetric liner wear in retrieved TKRs [8], and it is for contemporary prosthesis designs (LCS®, P.F.C.® Sigma®, Sigma® Rotating Platform; DePuy-Synthes, West Chester, PA, USA) (Table 3). Other studies inferred wear from insert thickness measurements or from radiographs [3, 9] (Table 3).

The 50% lower wear rate of the TKR inserts compared with the THR liners for regular wear (no delamination) may be a result of the lower degree of multidirectional motion in the knee [18, 31]. This comparison entailed adjusting the wear rates to a patient age of 70 years to account for age dependence, and included only active patients. Given that wear particles from tibial wear tend to be larger than those from acetabular liners made from historical PE, approximately by a factor of three [33], the

lower wear rate for knees suggests that the number of submicron particles generated from knee wear could be more than an order magnitude lower than for hips, consistent with the lower incidence of wear-induced osteolysis reported for knees [11, 12].

We found a TKR/THR wear rate ratio of approximately 0.5 for HG and HG II THR liners and MG II TKR inserts made from the same PE implanted at approximately the same time by the same group of surgeons. This ratio is for active patients and excludes delaminated tibial liners. The lower TKR wear rate and assumed subsequent lower particle burden is in line with the lower incidence of osteolysis in TKRs compared with THRs [11, 12]. Although we used components made from historical PE in this study, the approach we used to evaluate wear of tibial inserts also can be applied to contemporary retrieved tibial inserts. Given the high local stresses and the possibility of edge loading on tibial inserts, there is a question regarding whether highly crosslinked PE is necessary in TKRs, or if moderately crosslinked PE would be sufficient to mitigate wear and osteolysis. Our findings, in conjunction with the lower incidence of osteolysis in TKR compared with THR components [12], suggest a moderately crosslinked PE could be sufficient. This hypothesis could be investigated by applying the methods used herein on a cohort of contemporary implants made from crosslinked PEs.

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