Oxidized Zirconium versus Cobalt-Chromium in TKA: Profilometry of Retrieved Femoral Components

Thomas J. Heyse MD, Marcella E. Elpers BS,
Danyal H. Nawabi MD, Timothy M. Wright PhD,
Steven B. Haas MD

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Abstract

Background Oxidized zirconium (OxZr) was introduced as an alternative bearing for femoral components in total knee arthroplasty (TKA) in an attempt to reduce wear compared with conventional cobalt-chromium (CoCr) alloys.

Questions/purposes The aim of this study was to compare matched pairs of retrieved OxZr and CoCr components using surface profilometry; specifically, we sought to compare the surface roughness of (1) retrieved OxZr TKA components with retrieved CoCr components; (2) the medial versus the lateral femoral condyles of retrieved components; and (3) unimplanted OxZr TKA components with unimplanted CoCr components.

Methods Ten retrieved posterior-stabilized Genesis II TKA with OxZr femoral components were identified and matched to retrieved CoCr femoral components by duration of implantation, patient age, and body mass index. A noncontact white light interferometer was used to evaluate surface roughness. One pristine, unimplanted component of each design was analyzed as a control.

Results The retrieved components showed significantly ($p < 0.0001$) lower roughness for the OxZr components than the CoCr components. CoCr retrievals showed a significantly greater average surface roughness on the medial condyle. No difference was found between the condyles of the OxZr components. The pristine CoCr implant had a

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained. This work was performed at the Hospital for Special Surgery, New York, NY, USA.

T. J. Heyse
Department of Orthopedics and Rheumatology, University
Hospital Marburg, Marburg, Germany

M. E. Elpers, T. M. Wright (✉)
Department of Biomechanics, Hospital for Special Surgery,
535 East 70th Street, New York, NY 10021, USA
e-mail: wrightt@hss.edu

D. H. Nawabi, S. B. Haas
Adult Reconstruction & Joint Replacement Division, Hospital
for Special Surgery, New York, NY, USA

significantly lower surface roughness than the pristine OxZr component.

Conclusions CoCr roughens significantly more in situ compared with OxZr components.

Clinical Relevance Bearing surfaces are typically damaged in vivo. The extent of damage is variable between patients and implants; however, rougher surfaces should be associated with more wear. Whether the differences observed in our study prove meaningful requires long-term clinical data.

Introduction

Traditional TKA bearing surfaces consist of cobalt-chromium alloys (CoCr) on ultrahigh-molecular-weight polyethylene (UHMWPE) for the femoral and tibial surfaces, respectively. Failure of these articulations can be attributed to UHMWPE wear, which accounted in one study for more than 44% of long-term TKA revisions [26]. Oxidized zirconium (OxZr) was introduced as an alternative femoral bearing surface with the intent to reduce UHMWPE wear [20].

The properties and the manufacturing process of OxZr have been described in detail [11]. In vitro laboratory studies showed its advantages in reducing UHMWPE wear and damage in comparison with conventional CoCr alloys [4, 15, 27]. Similarly, a retrieval study revealed less surface damage on UHMWPE components that articulated against OxZr than components paired with CoCr [12]. Several series have compared OxZr TKA components with conventional bearing surfaces [14, 17, 18]; however, superiority of OxZr has not been demonstrated in terms of better implant survival, at least at midterm followup.

Current literature suggests that the better in vitro wear performance of OxZr is related to its superior scratch resistance. Wear simulator data indicate that UHMWPE wear increases when the CoCr femoral countersurface is scratched [7]. Conversely, knee simulator studies showed that the surface roughness of the OxZr is maintained during testing [28]. Similarly, retrieval analysis of OxZr femoral components showed little surface damage [12].

In vivo data on OxZr performance based on retrieval analysis are scarce. In two prior studies, we used a subjective, visual score when inspecting retrieved OxZr and CoCr femoral components [12, 13]. In the current study, we limited our selection of retrieved femoral implants to a single design and manufacturer to focus the comparison between implants based primarily on the bearing material: OxZr versus CoCr. We used three-dimensional surface profilometry, a highly accurate technique used in previous studies of CoCr components [19, 23–25], to provide objective measurements of the surface roughness of the components.

In this report, we sought to compare the surface roughness of (1) retrieved OxZr TKA components with retrieved CoCr components; (2) the medial versus the lateral femoral condyles of retrieved components; and (3) unimplanted OxZr TKA components with unimplanted CoCr components.

Materials and Methods

Ten retrieved posterior-stabilized Genesis II TKA (Smith & Nephew, Memphis, TN, USA) with an OxZr femoral component were identified from our ongoing institutional review board-approved implant retrieval program. From our cohort of retrieved TKAs, we selected an additional 10 conventional CoCr femoral components that were matched to the OxZr components by duration of implantation (within ± 6 months), body mass index (within ± 5 kg/m²), and patient age (within ± 10 years). For the remaining 10 pairs, no significant differences were found between the OxZr and CoCr groups in terms of patient demographics (Table 1). Revision diagnoses were similar between the groups as well with most patients revised for stiffness (Table 1). All components had been implanted between 1999 and 2009.

All implants were cleaned with acetone before profilometry analysis. A white light noncontact interferometric profiler (MicroXAM Optical Profiler; ADE PhaseShift, Tuscon, AZ, USA) was used to measure the average surface roughness (S_a), the maximum peak to peak height (S_y), the 10-point height (S_z) roughness, and the surface skewness (S_{sk}) (Fig. 1). These parameters were chosen to best describe the topography of the bearing surface and are the same as have been used in previous retrieval analyses involving similar methods [1–3, 16, 19, 23–25]. Sixty measurements (four rows of 15 points, each point covering 600×800 μ m of the component's bearing surface) were taken per condyle, approximately at the location of contact during 30° of flexion (Fig. 2) as suggested by Que et al. [24, 25]. One pristine, unimplanted OxZr and one pristine CoCr component were measured to provide an estimate of the initial roughness before implantation.

Median values and first and third quartile ranges for each roughness parameter (S_a , S_y , S_z , S_{sk}) were calculated for the OxZr and CoCr femoral components. Before calculation of the surface roughness parameters, a global plane correction algorithm was used to subtract the macroscopic curvature from each scan. We examined the pristine only, retrieved only, and retrieved minus pristine (as an approximation of the change in roughness in vivo) for each material and each condyle. Further investigation included ranking the in vivo change values for each roughness parameter from lowest to highest. This represented the height profile distribution of the median surface roughness for each condyle and material.

Table 1. Demographic patient data for the 10 pairs of oxidized zirconium (OxZr) and cobalt-chromium (CoCr) components

Variable	CoCr	OxZr	p value
Female	4	7	0.37
Right	4	4	–
Length of Implantation (months)	32.3 ± 28.3	29.6 ± 12.5	0.71
Body mass index (kg/m ²)	31.1 ± 6.1	28.2 ± 3.6	
Age (years)	62.0 ± 12.0	58.1 ± 10.1	
Reasons for revision			
Stiffness	4	6	
Loosening	2	1	
Instability	–	1	
Infection	3	–	
Malposition	–	1	
Fracture	1	–	
Other	–	1	

Values are number or mean ± SD.

Fig. 1 This plot shows the definitions of the measured surface roughness parameters (S_a , S_y , and S_z). S_a is the average surface roughness. S_y is the maximum peak-to-peak height. S_z is the 10-point height average that takes the five highest peaks and five lowest valleys to compute the surface parameter [3]. These parameters are typically reported in terms of nanometers (nm) or micrometers (μm).

General estimating equation models were used, which allowed for adjusting the roughness data for age, sex, and length of implantation, thus indicating differences in roughness both between CoCr and OxZr materials and between the medial and lateral condyles for each material [10, 21]. A p value of < 0.05 was assumed to signify significant differences.

Fig. 2 Profilometry measurements were taken across the condyles at a location (the boxed region) signifying femorotibial contact at approximately 30° of flexion.

Results

The retrieved CoCr femoral components displayed more scratching (Fig. 3A) on gross visual assessment than the matched OxZr components (Fig. 3B). The profilometry measurements also displayed the greater roughness of the CoCr components (Fig. 4). For all four surface roughness parameters, the retrieved CoCr bearing surfaces were rougher than the OxZr bearing surfaces (S_a : $p < 0.001$, S_y : $p = 0.028$, S_z : $p = 0.036$, S_{sk} : $p < 0.001$) (Table 2). The overall average surface roughness for the retrieved CoCr implants was 83% greater than that of the retrieved OxZr implants. The maximum peak-to-peak height roughness and 10-point height roughness for the CoCr bearing surfaces were 39% and 33% greater than the OxZr bearing surface, respectively. The surface skewness (S_{sk}) of the bearing surfaces indicates that the retrieved CoCr surface contains a flat surface dominated by peaks ($0.32 \pm 1.04 \mu\text{m}$) compared with the retrieved OxZr surface, which is a flat surface comprised of pits or holes ($-0.33 \pm 2.53 \mu\text{m}$). No correlation with length of implantation was found between material or surface roughness.

The CoCr implants had greater surface roughness values for the medial condyle than the lateral condyle for the overall average surface roughness ($p = 0.014$) (Table 3). With the numbers available, no differences were detected between the medial and lateral condyles of the OxZr components.

The pristine CoCr implant had a lower surface roughness than the pristine OxZr for all three parameters. The surfaces of the retrieved OxZr implants were 20% rougher on average (S_a) than that of the pristine OxZr component, whereas those of the retrieved CoCr implants were 267% rougher on average than that of the pristine CoCr

Fig. 3A–B Light microscopy images (VHX-2000; Keyence, Elmwood, NJ, USA) of variations in surface scratching visible on the femoral component of a retrieved CoCr (A) as compared with an OxZr femoral TKA component (B).

Fig. 4A–D Surface topography plots of a matched pair show the differences between a severely roughened CoCr (A) component with extreme carbide peaks and scratching and the matched severely

roughened OxZr component (B). Another set of topography plots shows the difference between a minimally roughened CoCr (C) and the matched minimally roughened OxZr component (D).

component. Similar results were seen for the maximum peak-to-peak height and 10-point height roughness with an 84% and 87% increase in vivo for the CoCr bearing surfaces and a 12% and 24% increase in maximum peak-to-peak roughness for the OxZr bearing surfaces, respectively. For all four parameters, the retrieved CoCr bearing surfaces were rougher than their OxZr counterparts, indicating that the CoCr bearings roughened more in vivo because the CoCr pristine surface was smoother than the OxZr counterpart (Table 2). The surface of the pristine CoCr component was disrupted by hard carbide peaks (Fig. 5), whereas the pristine OxZr surface showed a more uniform distribution of shallow peaks and valleys (Fig. 6).

Discussion

The smoother surfaces of the retrieved OxZr implants as compared with their matched CoCr counterparts were expected given data from earlier knee simulator studies [28] and from our subjective visual inspection of these types of retrieved femoral components [12, 13]. Similar studies showed that CoCr retrievals were an order of magnitude rougher than pristine controls [25]. This roughening might explain why UHMWPE inserts paired with CoCr exhibit more surface damage than those paired with OxZr [12] and produce less UHMWPE wear in in vitro studies [4, 15, 27].

Our study had several limitations. Like with all retrieval analyses, this work was biased toward the study of failed components and thus may not be representative of well-functioning TKAs. Another limitation is that the cohort

Table 2. Surface roughness of cobalt-chromium (CoCr) and oxidized zirconium (OxZr) pristine and retrieved components

Parameters	CoCr		OxZr		p value
	Pristine	Retrieved	Pristine	Retrieved	
S_a	0.04 ± 0.01	0.21 ± 0.21	0.05 ± 0.00	0.15 ± 0.39	< 0.001
S_y	0.89 ± 0.23	4.28 ± 5.24	1.19 ± 0.73	3.90 ± 11.00	0.028
S_z	0.71 ± 0.11	4.04 ± 5.08	0.91 ± 0.28	3.73 ± 11.01	0.036
S_{sk}	0.97 ± 0.75	0.32 ± 1.04	-0.85 ± 0.95	-0.33 ± 2.53	< 0.001

Mean $\pm$ SD reported for each parameter; S_a = average surface roughness; S_y = maximum peak-to-peak height; S_z = 10-point height average that takes the five highest peaks and five lowest valleys to compute the surface parameter; S_{sk} = surface skewness that describes the asymmetry of the height distribution histogram. All values reported in micrometers. p value indicates difference between retrieved CoCr and OxZr surface parameters as determined by the generalized estimating equation analysis.

Table 3. Retrieved cobalt-chromium (CoCr) and oxidized zirconium (OxZr) surface roughness parameters by condyle

Parameters	CoCr		OxZr		p value
	Medial	Lateral	Medial	Lateral	
S_a	0.24 ± 0.24	0.18 ± 0.17	0.16 ± 0.51	0.15 ± 0.20	0.014
S_y	4.59 ± 5.20	3.96 ± 5.25	-0.60 ± 1.50	-0.06 ± 3.23	N/A
S_z	4.25 ± 4.83	3.83 ± 5.31	3.95 ± 14.20	3.84 ± 6.38	N/A
S_{sk}	0.33 ± 1.17	0.31 ± 0.88	3.81 ± 14.22	3.66 ± 3.36	N/A

Mean $\pm$ SD reported for each parameter; S_a = average surface roughness; S_y = maximum peak-to-peak height; S_z = 10-point height average that takes the five highest peaks and five lowest valleys to compute the surface parameter; S_{sk} = surface skewness that describes the asymmetry of the height distribution histogram. All values reported in micrometers. p value indicates difference detected between material and condyle combined as determined by the generalized estimating equation analysis; N/A = not available.

Fig. 5 Three-dimensional surface profile of the pristine CoCr implant showed a smooth surface disrupted by extreme carbide peaks. **Fig. 6** Three-dimensional surface profile of the pristine OxZr implant showed a uniform distribution of peaks and valleys, giving it a spongy-like appearance.

was relatively small with a short length of implantation as a result of the limited numbers of available OxZr components in our retrieval system. We tried to minimize this

limitation by matching the OxZr and CoCr retrieved implants on the basis of clinical parameters that might influence roughness changes. We did not match our cohort

based on sex, because previous retrieval studies have not indicated that sex correlates with the extent or severity of damage or wear observed. Yet another limitation was the lack of radiographic alignment measurements, which might have explained some of the asymmetry that we found between the roughness of the medial and lateral condyles. Finally, the mean duration of implantation was short (average, 30 months), but this is consistent with the finding that more than half of all TKA failures occur within the first 24 months after surgery [26].

Adhesive and abrasive wear mechanisms are known to play a dominant role in UHMWPE damage in vivo [29]. Typically these wear mechanisms result in damage modes of scratching and burnishing on the UHMWPE bearing surface of retrieved total joint replacements. Both mechanisms are dominated by surface asperities, especially on the harder surface of the bearing couple. Although third-body wear particles can also influence and cause abrasive and adhesive wear, a key component is the roughness of the bearing material itself [22]. Therefore, a better understanding of the surface roughness of the CoCr and OxZr bearing surfaces may help explain wear and damage that occur in vivo. Another consideration of the differences in roughness between CoCr and OxZr surfaces is its impact on the biological response to debris released from the bearing surfaces. An in vitro particle analysis under abrasive conditions indicated that OxZr produces 42% fewer of the critical smaller UHMWPE particles than CoCr [5, 6, 8]. However, this finding was not substantiated in one in vivo report. In that study, Kim et al. reported on 100 patients undergoing simultaneous bilateral TKA, receiving an OxZr femoral component in one knee and a CoCr femoral component in the other at minimum 5-year followup [18]. Joint fluid was aspirated, and UHMWPE particles were analyzed using thermogravimetric methods and scanning electron microscopy. The mean weight, size, aspect ratio, and roundness of particles were similar between the OxZr and CoCr TKAs. Survivorship and clinical function in both groups showed no differences [18].

Our finding that the medial femoral condyles were more prone to roughening than lateral condyles in both materials (and significantly so for the CoCr components) is likely the result of the fact that most of the load passes through the medial compartment as has been documented in vivo in patients with instrumented TKAs [9, 30]. For adhesive and abrasive mechanisms, wear (and hence roughening) would be expected to increase with increased load.

In conclusion, our study demonstrates that surface characteristics of OxZr compared with traditional CoCr alloys make it more resistant against roughening in TKA. The strengths of our study were the matching of OxZr and CoCr femoral components to eliminate some of the effects of other parameters on the comparison and the use of

profilometry, which is a highly accurate, objective technique that eliminates the subjectivity of visual component inspection. Our finding was consistent with the better wear performance of OxZr as shown in several in vitro and retrieval studies [5, 6]. However, comparative clinical trials are required to determine whether these differences will influence long-term function or survival of these implants. Early reports, including one randomized trial at minimum 5-year follow-up [18], have not substantiated this difference in vivo. Whether the extent of variability between the surface roughness of the CoCr and OxZr components proves meaningful will require long-term clinical data and followup.

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