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Primary Knee

Ceramic Coating in Cemented Primary Total Knee Arthroplasty is Not Associated With Decreased Risk of Revision due to Early Prosthetic Joint Infection

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ABSTRACT

Background: Prosthetic joint infection (PJI) is one of the most frequent and devastating causes of short-term revision total knee arthroplasty (TKA). In vitro evidence suggests ceramic surfaces demonstrate resistance to biofilm, but the clinical effect of bearing surface modifications on the risk of PJI remains unclear. This premier registry-based study examines the influence of ceramic bearing surface coatings on the outcome in cemented primary TKA.

Methods: In total, 117,660 cemented primary TKAs in patients with primary osteoarthritis recorded in the German arthroplasty registry since 2012 were followed up for a maximum of 3 years. The primary endpoint was risk of revision for PJI on ceramic coated and uncoated cobalt-chromium-molybdenum femoral components. Propensity score matching for age, gender, obesity, diabetes mellitus, depression and Elixhauser comorbidity index, and substratification on common design twins with and without coating was performed.

Results: In total, 4637 TKAs (85.1% female) with a ceramic-coated femoral component were identified, 42 had been revised for PJI and 122 for other reasons at 3 years. No survival advantage due to the risk of revision for PJI could be determined for ceramic-coated components. Revision for all other reasons demonstrated a significant higher rate for TKAs with ceramic-coated components. However, the results of this were confounded by a strong prevalence (20.7% vs 0.3%) of metal sensitivity in the ceramic-coated group.

Conclusion: No evidence of reduced risk for PJI due to ceramic-coated implants in cemented primary TKA was found. Further analysis for revision reasons other than PJI is required.

The single most frequently documented cause of revision primary total knee arthroplasty (TKA) surgery in the early (3 year) postoperative phase is prosthetic joint infection (PJI) often due to biofilm producing micro-organisms [1–3].

Subsequently, there has been increasing interest in orthopedic materials and coatings with bacteriostatic properties. These include ceramic coatings of titanium nitride (TiN), titanium niobium nitride, and zirconium nitride (ZrN) whereby ceramic is applied as a thin film or layer. A special arc evaporation technique called physical vapor deposition is used to apply the ceramic layer in a high-vacuum chamber [4]. Thus, only the surface of the implant is modified, not the material properties of the substrate nor its kinematic functionality. Ceramics have been demonstrated in vitro to reduce the capacity for pathogens to build biofilm [5]. Research in bioengineering and materials, as well as dentistry, has shown that the nanostructure surface topography of ceramics, surface smoothness, and hydrophobicity influences bacterial adherence and biofilm formation [6–9]. At the same time diagnosis of metal

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sensitivity is increasing [10]. Following the disastrous outcome of metal-on-metal hip arthroplasty, patients and surgeons are wary of metallic implants with a cobalt-chromium-molybdenum (CoCrMo) component [11]. A recent EU directive includes that patients must be informed about the potential carcinogenic risk of cobalt [12]. Ceramic bearing surfaces are more biocompatible than metal surfaces and demonstrate improved tribology [13–17]. Consequently, widespread interest is growing for ceramic coatings and this is reflected in our observations in the German Arthroplasty Registry (EPRD) [18]. Specifically, categorization of implants with ceramic coating is a unique feature of the EPRD's implant library.

Despite in vitro evidence showing improved bacteriostatic properties and biofilm resistance of ceramic coatings, there is currently scant clinical evidence to support the argument for ceramic coatings in knee arthroplasty for the purpose of reducing PJI risk. Ceramic-coated knee components are not universally deployed and many institutions and surgeons remain skeptical about the indication for and the perceived advantages of ceramic coating. It is prudent to await large population studies prior to adoption of variations in arthroplasty components or techniques [19]. Data to date have been difficult to acquire, due to the limited distribution of ceramic-coated knee components worldwide. Given recent clinical publications demonstrating reduced risk of PJI for hip replacements with ceramic bearing surfaces [20–22], it was hypothesized that a reduction in revision rate for PJI for TKAs utilizing a ceramic bearing surface could be demonstrated. A short-term (3 year) cohort analysis of all TKAs under observation of the EPRD was conducted. Observation groups were divided into 2: those receiving ceramic-coated femoral components and those receiving uncoated CoCrMo femoral components. In order to account for potential confounding factors with respect to mechanical design and type of ceramic coating, a subanalysis was performed of the 3 most commonly implanted ceramic-coated designs. To minimize misclassification with respect to the outcome of PJI, a secondary endpoint for revision reasons other than PJI was considered.

Materials and Methods

Follow-Up, Data Collection, and Data Linkage

Data for this observational cohort study were collected from the EPRD [7]. This national registry is an initiative of surgeons from the German Society of Orthopedics and Orthopedic Surgery e.V. in cooperation with public health insurance companies AOK-Bundesverband GbR and Verband der Ersatzkassen e.V. vdek, covering approximately 65% of the German population, the German Medical Technology Association, and hospitals performing hip and knee arthroplasty [18,23–26]. Data collection is voluntary for all patients, hospitals, and public health insurers. Mandatory billing data provided by hospitals allow follow-up of patients who may otherwise have been revised at a hospital outside of the data collection system of the EPRD [18,25]. Excepting emergent procedures performed outside of Germany, the entire registry cohort is followed up via data linkage with the health insurer, thus establishing a closed system of audit and survival analysis between participating hospitals, insurers, and patients [18,25].

The electronic case report form (eCRF) variables influencing implant survival such as gender and age at index surgery were linked with insurance record data including depression, obesity, complicated diabetes, and the nonweighted version of the Elixhauser index [27,28]. Metal sensitivity was documented preoperatively and consists of a range of clinical and subjective syndromes including but not limited to dermatologically patch tested nickel allergy and contact dermatitis.

Table 1
Description of Categorical Variables by Ceramic Bearing Surface Coating Before and After PSM at 1:5 (Strata I).

Variable	Crude		After PSM 1:5			
	Uncoated		Coated		Uncoated	
Number of TKAs	113,023		4637		23,185	
Number of hospitals	614		219		597	
Number of trademarks	38		14		37	
Metal sensitivity[a]	367	0.3%	962	20.7%	123	0.5%
Considered covariates[b] for PSM						
Median age at index surgery (y) [Q1; Q3]	72 [64; 77]		67 [60; 75]		67 [60; 75]	
Gender (female)	74,644	66.0%	3945	85.1%	19,723	85.1%
Depression[c]	5686	5.0%	277	6.0%	1335	5.8%
Diabetes, complicated[c]	2219	2.0%	52	1.1%	208	0.9%
Obesity[c]	31,698	28.0%	1277	27.5%	6393	27.6%
Elixhauser index[c] (0)	15,189	13.4%	788	17.0%	3947	17.0%
Elixhauser index[c] (1-4)	92,598	81.9%	3666	79.1%	18,355	79.2%
Elixhauser index[c] (≥5)	5236	4.6%	183	3.9%	883	3.8%

PSM, propensity score matching; TKA, total knee arthroplasty; ICD-10, 10th International Classification of Diseases.

[a] Most influential selection—based on ICD-10 L23.0 (contact dermatitis caused by metals)—could not be meaningfully matched.

[b] Differences in covariates between comparison groups were minimized by propensity score matching at 1:5.

[c] Based on coding algorithms for defining comorbidities in ICD-10 from Quan et al [27].

Study Subjects

Completed data sets were extracted including data on revision procedures for 180,234 primary TKAs conducted between November 1, 2012 and March 31, 2019. Inclusion criterion for patients was a diagnosis of primary gonarthrosis (M17.0/M17.1) coded via 10th International Classification of Diseases (ICD-10) [29]. Patients with a potential for higher grade of mechanical instability, such as those with post-traumatic arthritis, following corrective osteotomy or having rheumatoid arthritis were excluded. Only fully cemented knee systems with a cruciate retaining or posterior stabilized design without additional varus-valgus constraint were included. Hinge systems and systems of higher constraint and those requiring augments were excluded. The implant design properties were verified by cross-referencing with the EPRD implant library, whereby each component is classified according to type, material substrate, dimensions, surface properties/modifications, constraint, and fixation variables [18,24,25]. Included subjects (n = 117,660) from 623 hospitals were divided into a cohort of 4637 TKAs with a ceramic-coated femoral articular surface and a comparison cohort of 113,023 TKAs with an uncoated (CoCrMo) femoral implant.

Ceramic coating was defined for the purposes of the study as being either of TiN, titanium niobium nitride, or ZrN. Materials such as Oxinium (oxidized zirconium), which is a ceramicized zirconium alloy component rather than a CoCrMo component with a ceramic coating, were excluded from this study. The ceramic coating itself may be varied by choice of material (eg, TiN or ZrN), thickness, or number and composition of layers. For the purposes of the principal crude analysis all ceramic coatings were considered as a single group. The material of the tibial tray and polyethylene were not taken into account in the analysis of this study.

Fourteen different designs (defined by trademark) from 7 different companies were identified (strata I) in the study population of patients receiving ceramic-coated femoral components. In the uncoated comparison group, 38 different trademarks from 20 companies were implanted.

Metal sensitivity was a strong patient selection factor for a ceramic-coated implant (20.7% in the coated group vs 0.3% in the uncoated group), but it was not the only reason for this implant

Table 2
TKA Designs With Ceramic-Coated Femoral Component in Follow-Up.

Trademark (Manufacturer)	Crude	Matched 1:3	
	Uncoated[a]	Coated[a]	Uncoated[b]
Columbus (Aesculap)	9407	1084	3252
Vanguard (Zimmer Biomet)	8849	756	2268
e.motion (Aesculap)	4759	1330	3990
BalanSys BICONDYLAR (Mathys)	2677	***327***	
EFK (OHST Medical Technology)	2463	***23***	
ACS (Implantcast)	***293***	866	
GEMINI SL (Waldemar Link)	625	***12***	
VEGA (Aesculap)	***448***	***166***	
AlloGen (OHST Medical Technology)	***276***	***12***	
SCORE (Amplitude)	***192***	***20***	
4Motion Kniesystem (Artiqo)	***108***	***16***	
ZEN (OHST Medical Technology)	***57***	***3***	
K-MOD (Corin)	***30***	***21***	
MRK (IO-International Orthopedics)	***22***	***1***	

TKA, total knee arthroplasty.
[a] Numbers were italicized and displayed in bold when less than 500 TKAs were under observation.
[b] Comprising numbers of matched design twins with a minimum of 500 TKAs in both arms.

choice. Excluding metal sensitivity, crude selection data demonstrate a selection preference for ceramic-coated implants for women (85% vs 66%), with a slightly younger age range of 67 years (interquartile range 60-75) vs 72 years (interquartile range 64-77). Following propensity score matching (PSM) on patient variables we arrived at 2 comparable cohorts based on treatment allocation (Table 1).

All 14 ceramic-coated components had a design twin in the uncoated group (Table 2). To account for the possibility that implant design could influence outcome, we substratified for the most frequently implanted designs with a minimum of 500 TKAs in both arms (strata II). Three designs from 2 different companies were identified: Columbus (Aesculap), Vanguard (Zimmer Biomet), and e.motion (Aesculap). Patient selection and strata subdivision are shown in the flowchart (Fig. 1).

Defining/Identification of Outcome

The primary endpoint was revision for PJI. A secondary endpoint of revision surgery for reasons other than PJI was included for completeness.

Revision was defined as removal or exchange components, accepting patella resurfacing on the same joint with or without inlay exchange, which is interpreted as complementary surgery for progression of the disease. Patients who did not require a revision prior to their death or amputation of the affected limb have been "censored" at that time. This means that up to the occurrence of the competing risk their outcome is still accounted, but no longer followed up, to avoid an underestimation of the revision rate.

PJI was flagged when "infection" was classified as reason for revision and was directly reported to the EPRD via eCRF or when reimbursement data coded ICD-10 T84.5 "Infection and inflammatory reaction due to internal joint prosthesis."

Statistical Methods

Data were analyzed considering crude implant survival rates over the first 3 years to maximize capture of perioperative infection.

To account for bias in patient selection for a particular treatment (ceramic coating or uncoated), PSM was applied on the variables of gender, depression, obesity, complicated diabetes, the nonweighted version of the Elixhauser index, and age at the time of operation [27,28]. The propensity scores were estimated using logistic regression modeling implemented in the R-function for covariable balanced propensity scores. Because metal sensitivity is the most influential selection indication for a ceramic-coated implant, it could not be meaningfully matched.

"Nearest neighbor" matching in a 2-step approach (1:5 on all designs and 1:3 on specific designs) was then performed, where each patient receiving a ceramic-coated femoral implant is assigned to 5 (respectively 3) patients with nearest propensity scores. R-function was used to conduct the statistical analysis [30].

Ethical Approval

This study was approved by the ethics committee of the medical school of the Kiel University (approval number D 473/11).

Results

Of 4637 TKAs in the coated group, 42 had been revised for PJIs and 122 for other reasons. For the 113,023 TKAs in the uncoated group, 868 had been revised for PJIs and 1549 for other reasons. The crude cumulative probability of revision (CPR) for PJI was not statistically significantly different for the ceramic-coated group with 1.2% (95% confidence interval [CI] 0.8-1.6) when compared with the uncoated group with 1.0% (95% CI 0.9-1.1). After PSM at 1:5 between cohorts the CPR remained statistically insignificant with the matched result for the uncoated group now being 0.9% (95% CI 0.7-1.0). The survival curve is consistent with that of revision due to PJI, in that 50% of revisions occur within 3 months of the index procedure. The CI for survival of TKAs with ceramic-coated femoral components is wider than that for uncoated components reflecting the comparative size of the cohorts. There is no survival advantage for ceramic-coated components at any time interval, with respect to the outcome of revision for PJI (Fig. 2).

The crude CPR for causes other than PJI up to 3 years of follow-up showed a significant difference between the coated group with 3.9% (95% CI 3.1-4.6) when compared with the uncoated group with 2.0% (95% CI 1.8-2.1). After matching at 1:5 between cohorts the CPR remained statistically significant with the matched result for the uncoated group now being 2.1% (95% CI 1.9-2.4). The difference in survival appears early and is sustained (Fig. 3).

The propensity score matched (1:3) CPR comparing femoral articular bearing surfaces of the 3 most utilized designs demonstrated no survival advantage for ceramic coating at any stage throughout the 3-year follow-up for primary TKA with respect to revision for PJI (Table 3). The homogeneity across 3 different component designs—comprising more than 70% of all trademark twins in follow up—supports the findings in the crude analysis.

Discussion

This registry-based study aims to investigate the influence of ceramic surface coating of femoral components in primary TKA on risk of PJI.

Germany is one of the biggest consumers of ceramic-coated arthroplasty components. In 2018, 4.7% (n = 5599) of all registry-documented femoral components implanted were ceramic coated and the incidence is increasing [18]. The data available from the EPRD enabled us to study one of the largest population cohorts worldwide. As far as we are aware, this is the only registry publication looking specifically at the influence of ceramic coating on PJI in TKA.

Identifying PJI among the study population was designed to over-ascertain cases in a 2-step approach. First, while entering

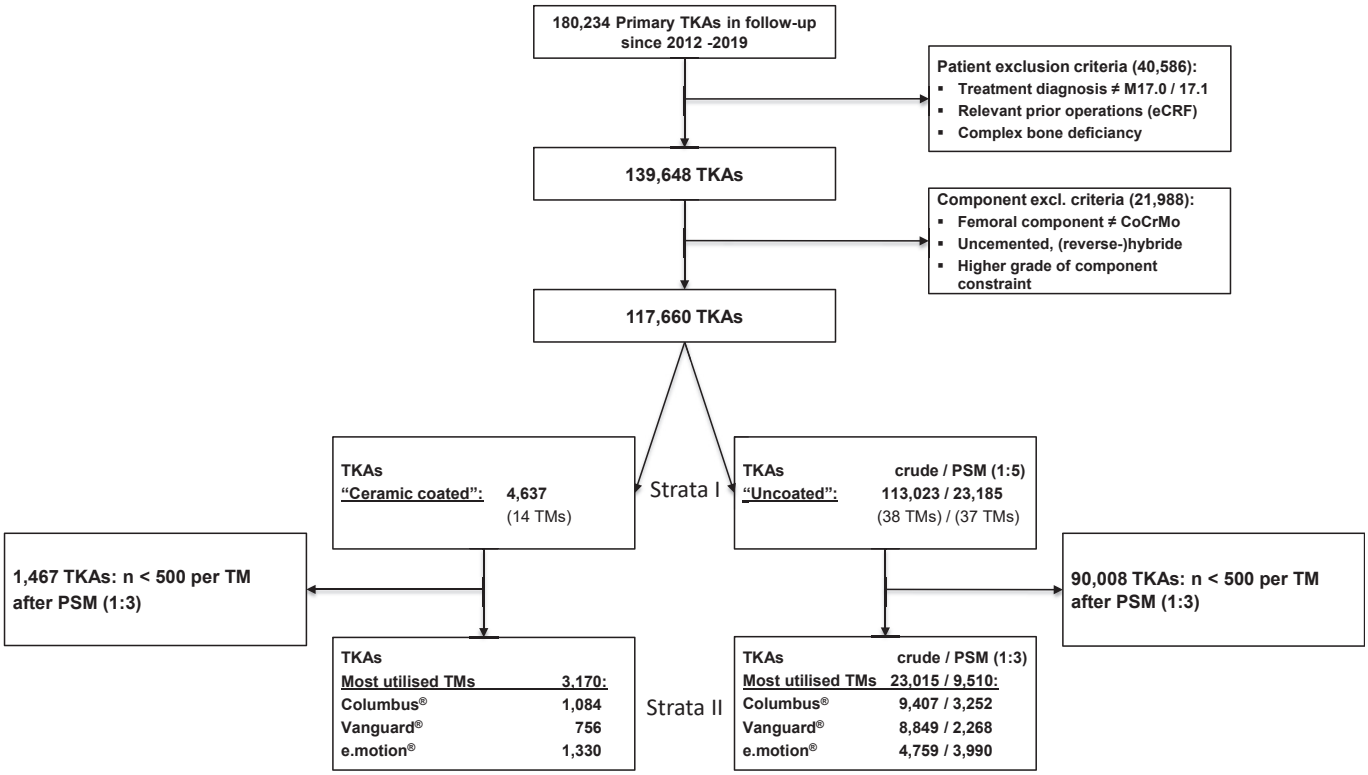

Fig. 1. Flowchart of patient selection and strata subdivision. eCRF, electronic case report form; TM, trade mark; TKA, total knee arthroplasty; PSM, propensity score matching.

cases into the EPRD database manually, surgeons are asked (eCRF) to classify the reason for revision. Second, cases with a PJI are identified PJI when reimbursement data coded ICD-10 T84.5. Even if surgeons may have wrongly assessed reason for revision before surgery, hospital billing based on all information available at discharge of patients may include the right diagnoses. Nonetheless, registries tend to underrate PJI in total hip and knee arthroplasty [31]. In most registries, diagnosis of PJI is established before or directly after surgery; however, in some cases microbiological and histological results become positive days after surgery when diagnosis is already reported to the database of the registry or not changed subsequently. Within the current study CPR for PJI of 1.2%

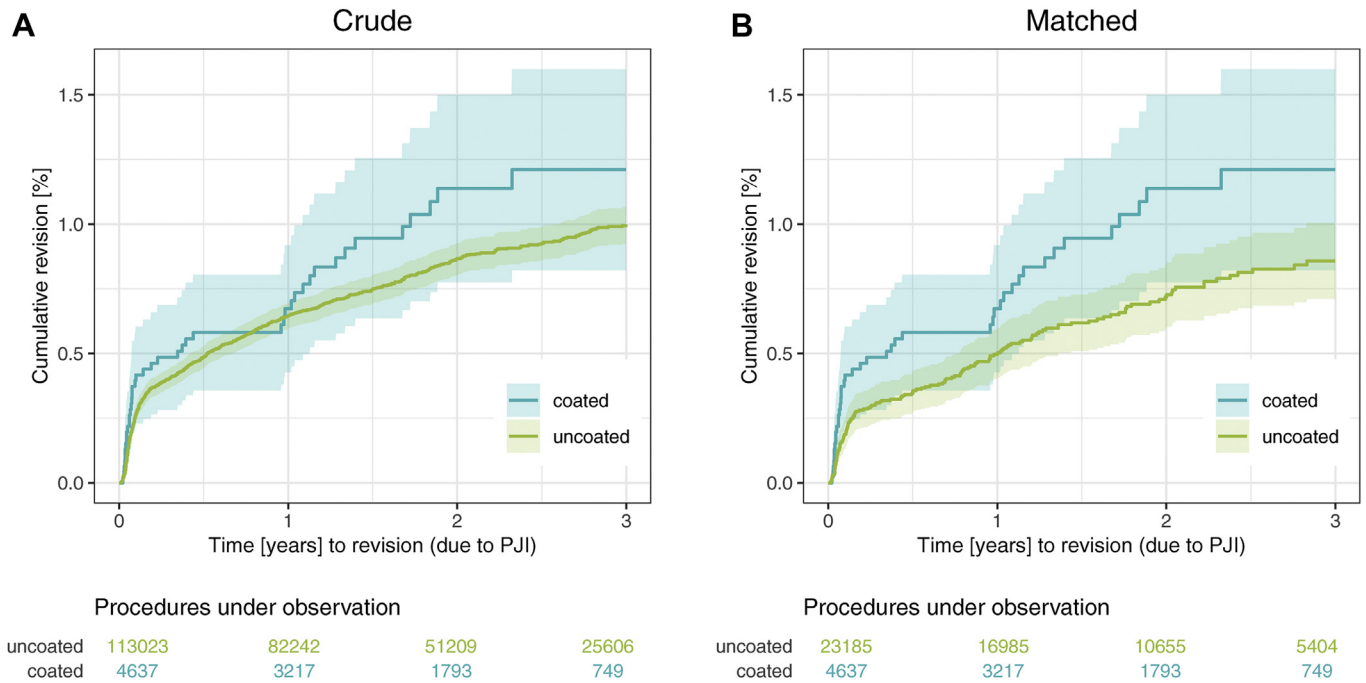

Fig. 2. Cumulative probability of revision—Kaplan-Meier [95% CI]: (A) crude and (B) after PSM 1:5—for PJI, comparing TKA systems with ceramic coated and uncoated femoral components (strata I). CI, confidence interval; PJI, periprosthetic joint infection.

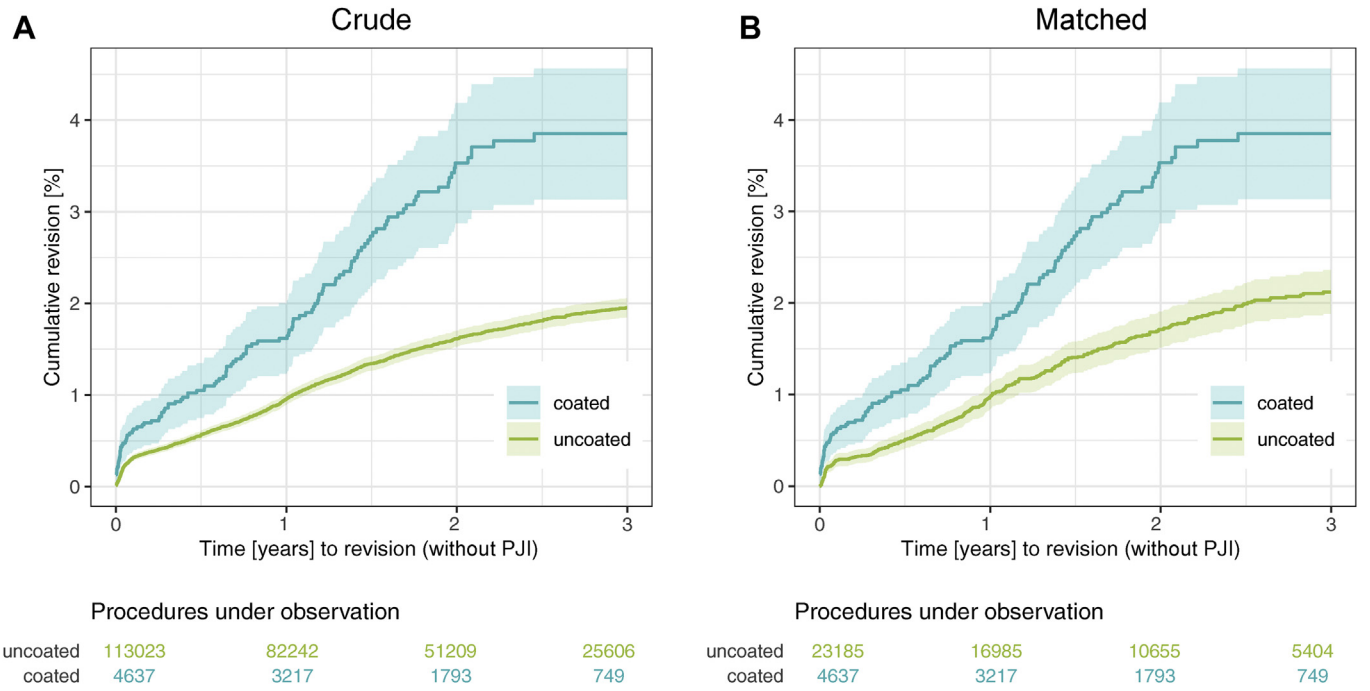

Fig. 3. Cumulative probability of revision—Kaplan-Meier [95% CI]: (A) crude and (B) after PSM 1:5—without PJI, comparing TKA systems with ceramic coated and uncoated femoral components (strata I).

of the ceramic-coated group, and 1.0% with up to 3 years follow up of primary TKA represented a revision probability due to early PJI consistent with that reported by other international registry publications [32,33]. The analysis was arbitrarily limited to 36 months to include revision of low-grade chronic PJI, in alignment with previous published cut-offs [34,35].

Polyethylene is widely acknowledged as a significant factor in hosting biofilm forming bacteria in arthroplasty [36], but considering that polyethylene was consistent in both analytical arms of the study, it was not considered to confound the results. The material of the tibial component was not included, as the femoral component contributes to the greatest surface in the articulation. Determination of an inverse dose-response relationship between the proportion of articular ceramic and PJI risk could add weight to the hypothesis that ceramic bearing surfaces are protective.

In contrast to the observations for the primary endpoint, an early and persistent survival advantage for uncoated femoral components is clearly displayed. The reasons for this strong association are concerning. First, consideration must be given to mechanical reasons for failure. Similarly to the increased revision rate observed with Oxinium femoral components [37], it could be postulated that ceramic coating predisposes to early revision. However, current international registry data do not support this showing equivalent survival results for, for example, the ceramic-coated Columbus variant [38].

One of the most significant differences between the 2 cohort groups in the study was metal sensitivity status L23.0, ICD 10 (20.7% vs 0.3%). In this study, the diagnosis of metal sensitivity included self-registered “metal sensitivity” and was not confirmed with laboratory or patch testing. A prevalence rate of 1.1% was documented, consistent with reports in the literature [39]. There is evidence suggesting the prevalence is linked to metal exposure [40], and accordingly, metal sensitivity can be increasingly anticipated in the setting of revision surgery. Female patients with exposure to nickel containing jewellery are more likely to have metal sensitivity, thus explaining the female selection bias for ceramic-coated

Table 3
CPR After PSM at 1:3 for PJI of the Most Frequently (n ≥ 500) Implanted Designs With Ceramic Coated and Uncoated Femoral Components (Strata II).

Trademark (Manufacturer)	Femoral Component	n	Number of Hospitals	Median Age at Primary TKA (y [Q1; Q3])	Gender (Female)	CPR (95% CI) and Numbers at Risk Since Primary TKA After…			*P*-Value
						1 y	2 y	3 y	
Columbus (Aesculap)	Uncoated	3252	85	66 [60; 73]	92%	0.5 [0.3; 0.8] [2368]	0.7 [0.4; 1.1] [1447]	0.9 [0.5; 1.3] [701]	.856
	Coated	1084	92	65 [58; 73]	92%	0.7 [0.2; 1.3] [751]	0.7 [0.2; 1.3] [446]	1 [0.2; 1.8] [197]	
Vanguard (Zimmer Biomet)	Uncoated	2268	62	67 [59; 75]	92%	0.5 [0.2; 0.8] [1673]	0.7 [0.3; 1.1] [1006]	0.9 [0.4; 1.3] [450]	.622
	Coated	756	57	67 [59; 75]	92%	0.5 [0; 1.1] [512]	1 [0.2; 1.8] [285]	1 [0.2; 1.8] [119]	
e.motion (Aesculap)	Uncoated	3990	59	70 [63; 77]	76%	0.4 [0.2; 0.6] [2818]	0.8 [0.4; 1.1] [1728]	0.9 [0.5; 1.3] [831]	.742
	Coated	1330	62	68 [60; 76]	80%	0.3 [0; 0.6] [945]	0.7 [0.2; 1.3] [498]	0.7 [0.2; 1.3] [185]	

CPR, cumulative probability of revision; PSM, propensity score matching; PJI, periprosthetic joint infection; TKA, total knee arthroplasty; CI, confidence interval.

knee components in this study. The potential positive influence of reduced polyethylene wear preventing metal ion release was considered a long-term outcome and therefore not relevant to the results of this short-term study.

Metal sensitivity has complicated the analysis of failure rates particularly of TKAs [41]. The definition of PJI T84.5, ICD-10 being "infection and/or inflammatory reaction due to internal joint prosthesis" encompasses the clinical spectrum of documented metal sensitivity reactions being "impaired wound and fracture healing, infection-mimicking reactions, effusions, pain and loosening" [42]. For the purposes of data collection by the EPRD, metal sensitivity is defined as contact dermatitis, and as such is open to subjective interpretation from patients as well as clinicians [43]. Accurate diagnosis of true metal sensitivity requires an interdisciplinary approach with immunological and dermatological interpretation of patch testing, histology, and lymphocyte transformation testing [42,44].

It has been argued that the widespread use of sonication improving the sensitivity of microbiological assessment of failed arthroplasty could result in failures previously ascribed to metal sensitivity, now being diagnosed as infection [45]. A substratification of results based on accurately diagnosed metal sensitivity status was beyond the scope of this study.

In contrast to the primary endpoint of revision for PJI, "revision for all other reasons" includes nonspecific reasons for revision, such as unresolved pain and mechanical failure. The authors postulate that ceramic coating may be a proxy for factors contributing to early failure such as nonroutine surgeon's use or patient-specific risk factors. The early revision rate is of concern and requires further specific analysis.

Limitations

1. These findings must be interpreted carefully given the limitation that the coding practices differ among hospitals, introducing the potential for outcome misclassification, and therefore observation bias. Countering this is the advantage of the robustness of data trends observed, even if the absolute numbers might not be totally accurate.
2. We used revision as our endpoint, which fails to account for patients suffering under a low-grade infection with a poorly functioning knee arthroplasty.
3. We have no information about the microbiological diagnosis in our study population.
4. Follow-up time limited to 3 years. In comparison to clinical studies reporting performance of ceramics in THA, the follow-up continued up to 15 years [20,22]. It is possible that following our study cohort over the next 10 years we will see a similar effect of improved survival with ceramic-coated components and our results may help to delineate the role of ceramic in preventing "chronic" PJI, or late secondary blood-borne contamination. However, given that the majority of PJI in TKA is expected to occur within the acute follow-up period, we consider that our study cohort of elective TKA patients with focused short-term follow-up provides valuable insight into the natural history of acute PJI.
5. With regard to the main analysis (strata I) based on all available designs we cannot exclude prosthetic design factors from having an influence on the failure rate, thus confounding the relationship between implant survival and bearing surface. However, the subanalysis of the 3 most utilized designs performed in this study could discern no clear trend to differential survival due to PJI between the compared ceramic coatings, nor implant designs.
6. We have performed no specific subanalysis of different ceramic coatings. There is significant variability in the process of ceramic coating, and potential for discrepancies in survival to arise.
7. Due to the overwhelming presence of metal sensitivity in the ceramic coating group, we were unable to conduct meaningful matching for this covariate, therefore our comparison groups still differ significantly by this confounding factor, and we cannot exclude that this has influence on our results.

Conclusions

In this (premier) first registry-based study of 4637 primary TKAs with ceramic-coated femoral articulation surface, we were unable to demonstrate a survival advantage with respect to revision for PJI in the short term.

The analysis of ceramic coated and uncoated groups for revision due to causes other than PJI (secondary endpoint) demonstrated an early and persistent survival advantage for uncoated femoral components.

Considering the shortcomings of this study, we limit our conclusion to the statement that there is no clinical evidence to support the in vitro suggestion that ceramic-coated knee implants offer a survival advantage with respect to risk of PJI in the short term (3 years). We anticipate that with increasing case numbers and data collection over time, we will be able to report in the future with more accuracy on the survival of ceramic-coated knee components.

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References

[1] Nickinson RS, Board TN, Gambhir AK, Porter ML, Kay PR. The microbiology of the infected knee arthroplasty. Int Orthop 2010;34:505–10. https://doi.org/10.1007/s00264-009-0797-y.

[2] Lenguerrand E, Whitehouse MR, Beswick AD, Kunutsor SK, Foguet P, Porter M, et al., National Joint Registry for England WNI, the Isle of M. Risk factors associated with revision for prosthetic joint infection following knee replacement: an observational cohort study from England and Wales. Lancet Infect Dis 2019;19:589–600. https://doi.org/10.1016/S1473-3099(18)30755-2.

[3] Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR). Hip, knee & shoulder arthroplasty: annual report 2019. Adelaide. https://aoanjrr.sahmri.com/de/annual-reports-2019; 2019 [accessed 28.09.20].

[4] Baptista. Sputtering physical vapour deposition (PVD) coatings: a critical review on process improvement and market trend demands. Coatings 2018;8:402.

[5] Pilz M, Staats K, Tobudic S, Assadian O, Presterl E, Windhager R, et al. Zirconium nitride coating reduced *Staphylococcus epidermidis* biofilm formation on orthopaedic implant surfaces: an in vitro study. Clin Orthop Relat Res 2019;477:461–6. https://doi.org/10.1097/CORR.0000000000000568.

[6] Porporati AA, Spriano S, Ferraris S, Rimondini L, Cochis A. Ceramic materials show reduced bacteria biofilm formation, because of their surface chemico-physical properties. Orthop Proc 2016;98-B(SUPP_9):150. https://doi.org/10.1302/1358-992x.98bsupp_9.Ista2015-150.

[7] Lin X, Yang S, Lai K, Yang H, Webster TJ, Yang L. Orthopedic implant biomaterials with both osteogenic and anti-infection capacities and associated in vivo evaluation methods. Nanomedicine 2017;13:123–42. https://doi.org/10.1016/j.nano.2016.08.003.

[8] Mitik-Dineva N, Wang J, Mocanasu RC, Stoddart PR, Crawford RJ, Ivanova EP. Impact of nano-topography on bacterial attachment. Biotechnol J 2008;3:536–44. https://doi.org/10.1002/biot.200700244.

[9] Yeo IS, Kim HY, Lim KS, Han JS. Implant surface factors and bacterial adhesion: a review of the literature. Int J Artif Organs 2012;35:762–72. https://doi.org/10.5301/ijao.5000154.

[10] Schuttelaar MLA, Ofenloch RF, Bruze M, Cazzaniga S, Elsner P, Goncalo M, et al. Prevalence of contact allergy to metals in the European general population with a focus on nickel and piercings: the EDEN Fragrance Study. Contact Dermatitis 2018;79:1–9. https://doi.org/10.1111/cod.12983.

[11] van Lingen CP, Zagra LM, Ettema HB, Verheyen CC. Sequelae of large-head metal-on-metal hip arthroplasties: current status and future prospects. EFORT Open Rev 2016;1:345–53. https://doi.org/10.1302/2058-5241.1.160014.
[12] EFORT/MedTech. Cobalt in orthopaedic implants - joint statement of EFORT and MedTech Europe's Orthopaedic Sector Group. European Federation of National Associations of Orthopaedics and Traumatology (EFORT); 2018. https://www.efort.org/wp-content/uploads/2018/09/20180814_EFORT_Cobalt_Statement.pdf [accessed 28.09.20].
[13] Fabry C, Zietz C, Baumann A, Ehall R, Bader R. High wear resistance of femoral components coated with titanium nitride: a retrieval analysis. Knee Surg Sports Traumatol Arthrosc 2018;26:2630–9. https://doi.org/10.1007/s00167-017-4578-7.
[14] Zietz C, Kluess D, Bergschmidt P, Haenle M, Mittelmeier W, Bader R. Tribological aspects of ceramics in total hip and knee arthroplasty. Semin Arthroplasty 2011;22:258–63. https://doi.org/10.1053/j.sart.2011.10.006.
[15] Puente Reyna AL, Fritz B, Schwiesau J, Schilling C, Summer B, Thomas P, et al. Metal ion release barrier function and biotribological evaluation of a zirconium nitride multilayer coated knee implant under highly demanding activities wear simulation. J Biomech 2018;79:88–96. https://doi.org/10.1016/j.jbiomech.2018.07.043.
[16] Reich J, Hovy L, Lindenmaier HL, Zeller R, Schwiesau J, Thomas P, et al. [Preclinical evaluation of coated knee implants for allergic patients]. Orthopade 2010;39:495–502. https://doi.org/10.1007/s00132-009-1581-9.
[17] Grupp TM, Giurea A, Miehlke RK, Hintner M, Gaisser M, Schilling C, et al. Biotribology of a new bearing material combination in a rotating hinge knee articulation. Acta Biomater 2013;9:7054–63. https://doi.org/10.1016/j.actbio.2013.02.030.
[18] German Arthroplasty Registry EPRD. German arthroplasty registry (Endoprothesenregister Deutschland - EPRD) - annual report 2019. Berlin. German Arthroplasty Registry (Endoprothesenregister Deutschland - EPRD); 2020. https://www.eprd.de/fileadmin/user_upload/Dateien/Publikationen/Berichte/EPRD_Jahresbericht_2019_EN_doppelseitig_F_Web.pdf [accessed 28.09.20].
[19] Anand R, Graves SE, de Steiger RN, Davidson DC, Ryan P, Miller LN, et al. What is the benefit of introducing new hip and knee prostheses? J Bone Joint Surg Am 2011;93(Suppl 3):51–4. https://doi.org/10.2106/JBJS.K.00867.
[20] Pitto RP, Sedel L. Periprosthetic joint infection in hip arthroplasty: is there an association between infection and bearing surface type? Clin Orthop Relat Res 2016;474:2213–8. https://doi.org/10.1007/s11999-016-4916-y.
[21] Bordini B, Stea S, Castagnini F, Busanelli L, Giardina F, Toni A. The influence of bearing surfaces on periprosthetic hip infections: analysis of thirty nine thousand, two hundred and six cementless total hip arthroplasties. Int Orthop 2019;43:103–9. https://doi.org/10.1007/s00264-018-4097-2.
[22] Madanat R, Laaksonen I, Graves SE, Lorimer M, Muratoglu O, Malchau H. Ceramic bearings for total hip arthroplasty are associated with a reduced risk of revision for infection. Hip Int 2018;28:222–6. https://doi.org/10.1177/1120700018776464.
[23] Hassenpflug J. The German arthroplasty register (EPRD). In: Structure, procedures and organisation. European Federation of National Associations of Orthopaedics and Traumatology (EFORT) European Arthroplasty Register (EAR); 2012. Paper presented at the EFORT Congress, Berlin, https://www.eprd.de/fileadmin/user_upload/Dateien/Publikationen/Artikel_und_Aufsaetze/2012_e_book_eprd.pdf [accessed 28.09.20].
[24] Blomer W, Steinbruck A, Schroder C, Grothaus FJ, Melsheimer O, Mannel H, et al. A new universal, standardized implant database for product identification: a unique tool for arthroplasty registries. Arch Orthop Trauma Surg 2015;135:919–26. https://doi.org/10.1007/s00402-015-2238-2.
[25] Jansson V, Grimberg A, Melsheimer O, Perka C, Steinbruck A. Orthopaedic registries: the German experience. EFORT Open Rev 2019;4:401–8. https://doi.org/10.1302/2058-5241.4.180064.
[26] Hassenpflug J, Liebs TR. [Registries as a tool for optimizing safety of endoprostheses. Experiences from other countries and the setup of the German arthroplasty register]. Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz 2014;57:1376–83. https://doi.org/10.1007/s00103-014-2057-6.
[27] Quan H, Sundararajan V, Halfon P, Fong A, Burnand B, Luthi JC, et al. Coding algorithms for defining comorbidities in ICD-9-CM and ICD-10 administrative data. Med Care 2005;43:1130–9. https://doi.org/10.1097/01.mlr.0000182534.19832.83.
[28] Elixhauser A, Steiner C, Harris DR, Coffey RM. Comorbidity measures for use with administrative data. Med Care 1998;36:8–27. https://doi.org/10.1097/00005650-199801000-00004.
[29] Anonymous. International classification of diseases. WHO collaborating centers. Epidemiol Bull 1998;19:7–11.
[30] Team RC. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2019.
[31] Witso E. The rate of prosthetic joint infection is underestimated in the arthroplasty registers. Acta Orthop 2015;86:277–8. https://doi.org/10.3109/17453674.2015.1042320.
[32] Zhu M, Ravi S, Frampton C, Luey C, Young S. New Zealand Joint Registry data underestimates the rate of prosthetic joint infection. Acta Orthop 2016;87:346–50. https://doi.org/10.3109/17453674.2016.1171639.
[33] Swedish Knee Arthroplasty Register (SKAR). Annual report 2019. Lund. http://www.myknee.se/pdf/SVK_2017_Eng_1.0.pdf; 2020 [accessed 28.09.20].
[34] Chun KC, Kim KM, Chun CH. Infection following total knee arthroplasty. Knee Surg Relat Res 2013;25:93–9. https://doi.org/10.5792/ksrr.2013.25.3.93.
[35] Postler A, Lutzner C, Beyer F, Tille E, Lutzner J. Analysis of total knee arthroplasty revision causes. BMC Musculoskelet Disord 2018;19:55. https://doi.org/10.1186/s12891-018-1977-y.
[36] Achermann Y, Vogt M, Leunig M, Wust J, Trampuz A. Improved diagnosis of periprosthetic joint infection by multiplex PCR of sonication fluid from removed implants. J Clin Microbiol 2010;48:1208–14. https://doi.org/10.1128/JCM.00006-10.
[37] Vertullo CJ, Lewis PL, Graves S, Kelly L, Lorimer M, Myers P. Twelve-year outcomes of an Oxinium total knee replacement compared with the same cobalt-chromium design: an analysis of 17,577 prostheses from the Australian Orthopaedic Association National Joint Replacement Registry. J Bone Joint Surg Am 2017;99:275–83. https://doi.org/10.2106/JBJS.16.00092.
[38] National Joint Registry for England, Wales, Northern Ireland and the Isle of Man (NJR). 16th Annual report 2019 (online report). Hemel Hempstead, Hertfordshire. https://reports.njrcentre.org.uk/Portals/0/PDFdownloads/NJR%2016th%20Annual%20Report%202019.pdf; 2019 [accessed 28.09.20].
[39] Thyssen JP, Menne T. Metal allergy—a review on exposures, penetration, genetics, prevalence, and clinical implications. Chem Res Toxicol 2010;23:309–18. https://doi.org/10.1021/tx9002726.
[40] Rosholm Comstedt L, Dahlin J, Bruze M, Akesson A, Hindsen M, Ponten A, et al. Prevalence of contact allergy to metals: nickel, palladium, and cobalt in Southern Sweden from 1995-2016. Contact Dermatitis 2020;82:218–26. https://doi.org/10.1111/cod.13422.
[41] Munch HJ, Jacobsen SS, Olesen JT, Menne T, Soballe K, Johansen JD, et al. The association between metal allergy, total knee arthroplasty, and revision: study based on the Danish Knee Arthroplasty Register. Acta Orthop 2015;86:378–83. https://doi.org/10.3109/17453674.2014.999614.
[42] Thomas P. Clinical and diagnostic challenges of metal implant allergy using the example of orthopaedic surgical implants: Part 15 of the Series Molecular Allergology. Allergo J Int 2014;23:179–85. https://doi.org/10.1007/s40629-014-0023-3.
[43] Walker T, Rutkowski L, Innmann M, Panzram B, Herre J, Gotterbarm T, et al. Unicondylar knee arthroplasty using cobalt-chromium implants in patients with self-reported cutaneous metal hypersensitivity. Bone Joint J 2019;101-B:227–32. https://doi.org/10.1302/0301-620X.101B2.BJJ-2018-0778.R1.
[44] Haddad SF, Helm MM, Meath B, Adams C, Packianathan N, Uhl R. Exploring the incidence, implications, and relevance of metal allergy to orthopaedic surgeons. J Am Acad Orthop Surg Glob Res Rev 2019;3:e023. https://doi.org/10.5435/JAAOSGlobal-D-19-00023.
[45] Kempthorne JT, Ailabouni R, Raniga S, Hammer D, Hooper G. Occult infection in aseptic joint loosening and the diagnostic role of implant sonication. Biomed Res Int 2015;2015:946215. https://doi.org/10.1155/2015/946215.