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Titanium Alloy Knee Implant Is Associated with Higher Bone Density over Cobalt Chromium: A Prospective Matched-Pair Case-Control Study

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Background: Little is known about the relationship between implant material and periprosthetic bone mineral density (pBMD) in total knee arthroplasty (TKA). The purpose of this study was to investigate the change in pBMD after TKA and to compare pBMD changes between two different implant materials.

Methods: A prospective matched-pair case-control study was conducted on 29 patients who underwent bilateral TKAs. The participants were randomly allocated to undergo cemented TKAs with a titanium nitride (TiN)-coated implant on one knee (TiN group) and a cobalt-chromium (CoCr) implant on the other knee (CoCr group). The pBMD was measured using dual-energy X-ray absorptiometry scans before surgery and at 1 and 2 years after surgery. The results were then compared between the two groups. The pBMDs at longer follow-ups (> 2 years) were estimated using simple radiographs (pBMDe).

Results: At 2 years after surgery, the pBMD significantly decreased in both groups at medial metaphysis of the tibia and anterior portion of the distal femur (all $p < 0.001$). The CoCr group showed a larger decrease in pBMD than did the TiN group in the medial and anterior metaphysis of the proximal tibia ($p = 0.003$ and $p = 0.046$, respectively). The pBMDe was significantly higher in the TiN group at the anterior portion of the distal femur 7 years after surgery ($p = 0.019$).

Conclusions: The pBMD significantly decreased 2 years after TKA in certain regions regardless of the implant material used. However, the decrease was significantly less in the TiN group in specific regions of the tibia and femur. The TiN implant was beneficial in preserving the periprosthetic bone stock after TKA.

Keywords: *Knee replacement arthroplasty, Bone density, Titanium alloy, Chromium alloy*

Total knee arthroplasty (TKA) often results in a decrease in periprosthetic bone mineral density (pBMD),[1-4] which sometimes leads to radiolucency around implants.[5] This decrease in pBMD may lead to implant failure, such as component subsidence. The mechanical property of the subchondral bone in the proximal tibia is an important biological determinant of loosening in TKA.[6] In a recent study,[7] occult osteoporosis was present in more than a third of patients with well-functioning TKAs.

Cobalt-chromium (CoCr) and titanium nitride (TiN) are the most widely used materials for TKA. According to a finite element study,[8] the difference in the elastic modulus of these two biomaterials affects the amount of stress shielding in TKA and subsequently leads to pBMD differences between the implant materials. Despite some growing evidence,[5,9] to date, there has been no prospective study comparing the pBMD of TKAs performed with the two different materials.

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The purpose of this study was to prospectively analyze the effect of implant material (CoCr and TiN) on pBMD after TKAs. In this study, the pBMD of the knees that used two different materials for TKAs was compared. One group of knees underwent cemented TKAs with CoCr, while the others did so with TiN. The authors hypothesized that the CoCr implant would be associated with a greater reduction in pBMD than the TiN implant.

METHODS

This prospective matched-pair case-control study was approved by the Institutional Review Board of Seoul National University Hospital (No. H-1103-045-354) and registered prior to the beginning of the study (No. KCT0000260). In a single, tertiary center, the patients who met the inclusion and exclusion criteria were screened for enrollment of the study on the day of admission (2 days before surgery). Informed consents were obtained from all of the participants. A priori power analysis was performed for sample size calculation (n = 29). A power analysis using estimates of mean BMD and standard deviation from the study of Abu-Rajab et al.[10] indicated that in a sample size of 26, with the power of 95% and a confidence level of 95%, a reduction in BMD of approximately 20% could be detected. Considering a dropout rate of 10%, the sample size was calculated as 29. From September 2011 to February 2012, 29 participants aged between 50 and 80 years, who underwent bilateral TKAs for degenerative arthritis, were enrolled (Fig. 1). Excluded from this study were participants with previous consumption of osteoporosis medication or long-term steroids, those who had previous knee surgery, and those with concomitant diseases (Parkinson disease, residual poliomyelitis, stroke, infection, etc.) that could have severely affected their physical recovery (n = 18). The demographic characteristics of the two groups (CoCr and TiN groups) were identical because all participants underwent bilateral TKAs with different types of prostheses on each knee. Out of the 29 patients, 2 were men and the average age, height, and body mass index were 70.5 ± 6.2 years, 153.2 ± 5.7 cm, and 26.1 ± 3.3 kg/m^2, respectively.

Surgery and Rehabilitation

Each participant underwent TKA with a TiN-coated prosthesis (Buechel and Pappas [B-P] Knee System; Korea Bone Bank, Seoul, Korea) on one knee and a CoCr prosthesis (LCS Knee System; Depuy, Warsaw, IN, USA) on the other knee. The side for each implant (right or left) was randomly allocated in each participant using a random number table, provided by an independent researcher (JYC). The sequence of implantation was also assigned randomly and the interval between TKAs was 1 week, except in 8 participants, whose interval was 1 to 3 weeks.

All operations were performed by a senior surgeon (MCL) with more than 20 years of experience in performing TKA. A midline incision, a standard paramedian approach, and the same surgical technique were used in all knees that underwent TKAs using two different materials (TiN and CoCr). The femoral and tibial components were both fixed with the same cement in both groups. Continuous passive motion exercise and full weight-bearing were allowed from the first day after surgery. No complications were observed during hospitalization.

Clinical Outcomes

Primary outcome

The primary outcome of the study was the relative pBMD of the proximal tibia and distal femur 2 years postoperatively. The pBMD was measured using dual-energy X-ray absorptiometry (DXA; Lunar Prodigy Advance, GE, Madison, WI, USA). DXA scans were performed before surgery and at 1 and 2 years postoperatively by assigned technicians (SWK and YJJ). Examinations were performed with the same unit with the same degree of calibration. Measurements were performed in both anteroposterior (AP) and lateral planes. AP scans were performed with the knee in full extension, while lateral scans were performed with the knee in 20° of flexion and neutral rotation.[11] Analyses

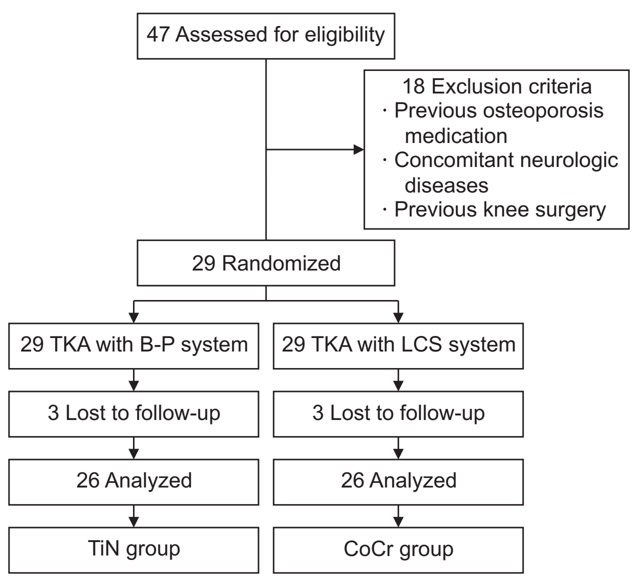

Fig. 1. Flowchart of the patients selected and grouped. TKA: total knee arthroplasty, B-P: Buechel and Pappas, TiN: titanium nitride, CoCr: cobalt-chromium.

of the measured values were performed by two independent observers (DHR and DWL). In the analyses, a total of 10 regions of interest (ROIs) were defined, 4 in AP scans (F1 and T1–3) and 6 in lateral scans (F2–5 and T4–5) as defined in a previous study (Fig. 2).[10] To ensure accuracy, using a postoperative DXA scan, the ROIs were set not to meet the implant, cortical bone, cement, and fibular head. These ROIs were equally applied to the preoperatively scanned image. Thus, identical regions could be analyzed for both replaced and non-replaced knees. Finally, pBMD was calculated in g/cm^2 using a DXA processing software (enCORE v.16; Encore Inc., Eagan, MN, USA). The pBMDs of the two different implants were compared before surgery and at 1 and 2 years postoperatively.

Secondary outcome

Since DXA scans were only performed until postoperative 2 years, pBMDs at longer follow-ups could only be inferred using simple radiographs. The ROIs were defined in the same manner[10] as in DXA scans, and the mean gray-scale value (Gm) of the pixels within each ROI was measured using an image processing software (ImageJ, National Institutes of Health, Bethesda, MD, USA). This estimated pBMD (pBMDe) was calculated using a formula introduced in a previous study[12]: pBMDe = 255 × (Gm of ROI – Gm of air) / (Gm of femoral component – Gm of air). Gm of air was measured on the same radiograph. The calculations were made separately by the two independent observers (DHR and DWL) and the reliability was measured. Hip-knee-ankle angle (HKA) and range of motion (ROM) of the knee were also measured as secondary outcomes by the independent observers. HKA was measured on standing AP long-leg radiographs as an angle between the mechanical axes of the femur and tibia and ROM was measured to the nearest 5°. Any complications including aseptic loosening, periprosthetic fracture, and infection were separately recorded.

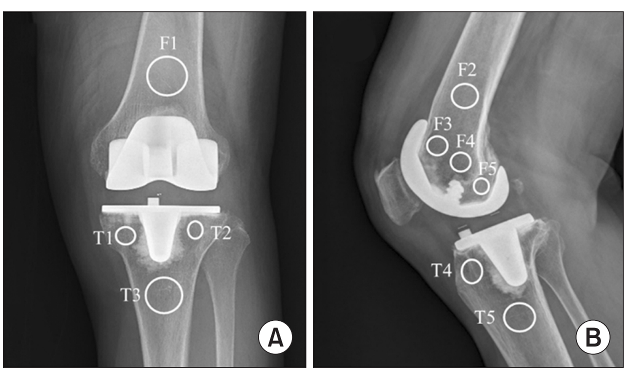

Fig. 2. Regions of interest in anteroposterior (A) and lateral (B) postoperative radiographs of a knee that underwent total knee arthroplasty with the Buechel and Pappas Knee system (titanium nitride implant).

Statistical Analysis

The Kolmogorov-Smirnov test and Shapiro-Wilk test were used to assess the normality of the distribution for all data. Continuous variables were presented as mean and standard deviation, and categorical variables were presented as frequency. Paired *t*-tests were applied to compare the two groups and to compare preoperative and postoperative data. To assess the reliability of pBMD and pBMDe, intraclass coefficients (ICCs) were calculated. The ICC for the AP scan was 0.993 (95% confidence interval [CI], 0.978–0.999), and the ICC for the lateral scan was 0.995 (95% CI, 0.977–0.999). Statistical analysis was performed using IBM SPSS ver. 25.0 (IBM Corp., Armonk, NY, USA). In all analyses, $p < 0.05$ was considered statistically significant.

RESULTS

Three patients were lost to follow-up during the 2 years; thus, a total of 26 patients were analyzed in the study. Preoperatively, all of the clinical parameters including the pBMD, pBMDe, HKA, and ROM were not significantly different between the groups (Table 1). Postoperatively, both groups showed a decrease in pBMD at the femur and tibia (Table 2). At 1 year after surgery, the postoperative

Table 1. Secondary Variables of the Two Groups

Variable	TiN Group (n = 26)	CoCr Group (n = 26)	*p*-value
Length of follow-up (yr)	8.3 ± 1.1	8.3 ± 1.1	-
Side of knee (right : left)	14 : 12	12 : 14	0.845
Hip-knee-ankle angle (°)			
Preoperative	9.5 ± 5.1	9.5 ± 5.2	0.995
Postoperative	1.4 ± 2.2	0.4 ± 1.8	0.054
Flexion contracture (°)			
Preoperative	9.5 ± 6.8	8.9 ± 5.2	0.536
Postoperative	0.3 ± 1.2	0.5 ± 1.5	0.573
Further flexion (°)			
Preoperative	126.0 ± 14.4	126.1 ± 15.4	1.000
Postoperative	124.0 ± 7.6	125.0 ± 7.9	0.211

Values are presented as mean ± standard deviation.
TiN: titanium nitride, CoCr: cobalt-chromium.

Table 2. Bone Mineral Density (g/cm²) Changes after Total Knee Arthroplasty

ROI		TiN Group						CoCr group						
		Baseline	1 yr	2 yr	Relative change of BMD (%; baseline to 1 yr)	Relative change of BMD (%; baseline to 2 yr)	*p*-value*	Baseline	1 yr	2 yr	Relative change of BMD (%; baseline to 1 yr)	Relative change of BMD (%; baseline to 2 yr)	*p*-value*	*p*-value[†]
AP	F1	0.891 ± 0.169	0.798 ± 0.171	0.812 ± 0.186	–10.4	–9.7	0.038[‡]	0.912 ± 0.193	0.798 ± 0.156	0.790 ± 0.191	–12.5	–13.4	0.000[‡]	0.131
	T1	1.039 ± 0.179	0.882 ± 0.148	0.866 ± 0.158	–15.1	–16.6	0.000[‡]	1.058 ± 0.213	0.778 ± 0.146	0.762 ± 0.165	–26.5	–26.9	0.000[‡]	0.003[‡]
	T2	0.744 ± 0.117	0.743 ± 0.096	0.729 ± 0.109	–0.1	–2.0	0.872	0.748 ± 0.121	0.742 ± 0.110	0.719 ± 0.110	–0.8	–3.9	0.488	0.110
	T3	0.881 ± 0.163	0.890 ± 0.161	0.850 ± 0.157	1.0	–3.5	0.166	0.872 ± 0.161	0.901 ± 0.160	0.890 ± 0.177	3.3	2.1	0.366	0.319
Lat	F2	0.837 ± 0.154	0.765 ± 0.177	0.773 ± 0.216	–8.6	–7.7	0.120	0.857 ± 0.185	0.799 ± 0.137	0.768 ± 0.180	–6.8	–10.5	0.001[‡]	0.980
	F3	0.839 ± 0.151	0.694 ± 0.166	0.695 ± 0.179	–17.3	–17.2	0.000[‡]	0.877 ± 0.150	0.688 ± 0.152	0.641 ± 0.196	–21.6	–26.9	0.000[‡]	0.980
	F4	0.828 ± 0.174	0.687 ± 0.175	0.721 ± 0.182	–17.0	–12.9	0.008[‡]	0.846 ± 0.142	0.670 ± 0.159	0.619 ± 0.192	–20.1	–26.8	0.000[‡]	0.093
	F5	1.061 ± 0.209	1.045 ± 0.245	1.059 ± 0.209	–1.5	–0.2	0.855	1.069 ± 0.206	1.036 ± 0.245	0.975 ± 0.280	–3.1	–8.8	0.125	0.273
	T4	0.592 ± 0.148	0.593 ± 0.158	0.623 ± 0.185	0.2	5.2	0.316	0.664 ± 0.137	0.533 ± 0.130	0.517 ± 0.170	–19.7	–22.0	0.000[‡]	0.046[‡]
	T5	0.501 ± 0.106	0.542 ± 0.139	0.548 ± 0.134	8.2	9.3	0.017[‡]	0.542 ± 0.159	0.560 ± 0.153	0.555 ± 0.184	3.3	2.5	0.900	0.776

Values are presented as mean ± standard deviation. Relative change of BMD (%) = [pBMD (postoperative) – BMD (baseline)] / BMD (baseline) × 100.
ROI: regions of interest, TiN: titanium nitride, CoCr: cobalt-chromium, BMD: bone mineral density, AP: anteroposterior, Lat: lateral, pBMD: periprosthetic bone mineral density.
*Paired *t*-test was used for comparing BMD between baseline and 2 years postoperatively within the groups. [†]Paired *t*-test was used for comparing BMD between the two groups at 2 year postoperatively. [‡]Statistically significant at $p < 0.05$.

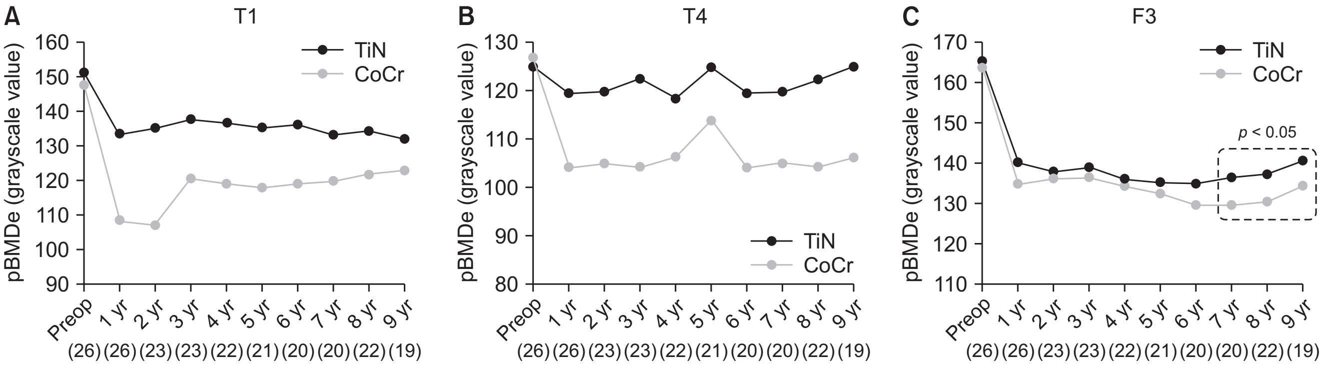

Fig. 3. Change of estimated periprosthetic bone mineral density (pBMDe) over the years in the region of interest: T1 (A), T4 (B), and F3 (C), the three areas with statistically significant difference. The numbers in parentheses denote the number of patients evaluated at each time point. TiN: titanium nitride, CoCr: cobalt-chromium, Preop: preoperative.

reductions in pBMDs were most prominent. The pBMD significantly decreased in 5 ROIs (F1, T1, F3–4, and T5) in the TiN group and in 6 ROIs (F1, T1, F2–4, and T4) in the CoCr group. At T1 and T4, pBMD was significantly larger in the TiN group than in the CoCr group 2 years postoperatively ($p = 0.003$ and $p = 0.046$, respectively).

As in pBMD, pBMDe significantly decreased postoperatively in both groups (Fig. 3). There was a significant difference in postoperative pBMDe between the two groups at specific sites. From the first year of surgery, the TiN group had significantly higher pBMDe at T1 and T4. Seven years postoperatively, pBMDe at F3 was significantly higher in the TiN group ($p = 0.019$). The postoperative HKA and ROM were not significantly different between the groups (Table 1). None of the participants underwent revision surgery during the follow-up period.

DISCUSSION

The most important findings of this prospective study are that (1) pBMD significantly decreased 2 years after cemented TKAs in certain regions (medial metaphysis of the tibia and anterior portion of the distal femur) regardless of the implant materials used and (2) the decrease in pBMD was significantly smaller with TiN than with CoCr in two specific regions: medial and anterior metaphysis of the tibia. These findings imply that after TKAs, the peri-implant bone stock weakens over the years and the TiN implant may be beneficial in preserving it. The pBMD can be influenced by many systemic factors such as mechanical loading, exercise, and medication.[4,13-15] These possible confounders are difficult to control because they cannot be objectively quantified. However, the confounding effect could be minimized in this study by using the two different materials on each knee of the same patients in the same period. In this study, the two implant systems (B-P and LCS) were selected for a couple of reasons. First, despite the differences in materials, the implants had very similar designs because the same surgeons (Buechel and Pappas) developed them with the intent to resemble each other.[16] Second, the LCS Knee System has shown excellent long-term survivorship with a low rate of revision.[17,18]

Many previous studies have reported a decrease in pBMDs around the tibia after TKA. Regner et al.[19] reported a mean decrease of 26% in pBMD in the medial condyle of the tibia during a 5-year follow-up of 38 uncemented TKAs. In a case series of 87 cemented TKAs, Saari et al.[20] demonstrated that the mean decrease in pBMD varied from 5% to 23% depending on the ROIs, and the decrease was most rapid during the first postoperative year in all ROIs. Similar to the results obtained in the above studies, our study showed that pBMD at the medial portion of the tibia (T1) decreased significantly in both groups at 2 years after TKA (16.6% and 26.9% for TiN group and CoCr group, respectively). The decrease in pBMD was most prominent during the first postoperative year, as was the case with previous studies.

Previous studies[21,22] have also revealed some decrease in pBMD in the distal femur after TKA. Mintzer et al.[22] reported that 68% of the study participants undergoing TKA had radiographic bone loss at the anterior portion of the distal femur within the first postoperative year. This showed no further progression over the years. Similar results were also found in studies that used DXA scans. Petersen et al.[23] reported a significant decrease in pBMD (range, 19%–44%) in the distal femur at 1 year of follow-up of 29 uncemented TKAs. Jarvenpaa et al.[4] assessed long-term pBMD changes in the distal femur in 69 cemented TKAs. The mean pBMD decrease during the 7-year follow-up period varied from 10.3% to 30.6%

depending on the ROI. Similar findings have also been reported in several studies.[1,3,10,24] Finite element models of the distal femur with a femoral component have predicted that the anterior aspect of the distal femur is the area of maximum stress shielding.[25,26] Similarly, in the present study, there was a marked decrease in pBMD in the distal femur during the first postoperative year (10.4% and 12.5% in the TiN group and CoCr group, respectively). In both groups, the largest reduction in pBMD was observed at F3 (behind the anterior flange of the implant).

To our knowledge, no study has prospectively examined the effect of implant material on postoperative pBMD to date. Martin et al.[9] first reported that the use of a CoCr implant was associated with a greater increase in medial bone loss of the tibia compared to TiN implants in TKAs. Recently, Yoon et al.[5] reported a similar finding that CoCr implants showed a higher incidence of radiolucent lines and a greater degree of BMD reduction in the medial tibial condyle compared to TiN implants. Unlike these two retrospective studies that estimated pBMD with simple radiographs, in the present prospective study, the authors quantified pBMD using DXA scans, which is considered the gold standard for the measurement of bone density. A previous study[27] reported that the error rate of DXA measurements in the knee was less than 3.3% regardless of the implant. The results of the present study are in accordance with those obtained in previous studies[5,9] in that the CoCr group showed a larger decrease in pBMD at the medial metaphysis of the tibia compared to the TiN group at postoperative 2 years (–26.9% vs. –16.6%, $p = 0.003$). This difference may be the result of stress shielding due to the different elastic moduli of the two materials, CoCr and TiN. The elastic moduli of these metallic biomaterials are larger than those of the bone (10–30 GPa), while CoCr (230 Gpa) has a higher elastic modulus than TiN (110 Gpa). Zhang et al.[8] found that pBMD was significantly influenced by implant material and stress shielding in a finite element model study comparing metal-backed and all-polyethylene tibial components in TKA. Although it was an ancillary analysis using pBMDe, our findings suggest that the long-term decrease in pBMD is also smaller at the anterior portion of the distal femur (in addition to the medial and anterior portions of the proximal tibia) when a TiN implant is applied.

Despite much evidence showing a decrease in pBMD after TKA, its association with periprosthetic fracture and implant loosening is still unclear. Probably owing to a relatively short follow-up period, none of the participants in this study underwent revision surgery due to loosening or fracture. However, Petersen et al.[6] showed that pBMD and tibial component migration were strongly correlated. Less migration of the tibial component was observed in knees with higher pBMD. Similarly, the decrease in pBMD at the anterior portion of the distal femur may be an important determinant of periprosthetic fracture and loosening of the femoral component after TKAs. As DXA scan is the gold standard for diagnosing osteoporosis, pBMD using DXA scan may well reflect the bone status around the prosthesis in TKAs. Thus, relative preservation of pBMD in the knees that had TiN implants may lead to a decrease in implant loosening or periprosthetic fracture. Consequently, TiN implants may be more beneficial to certain populations such as osteoporotic patients.

The result of the present study implies that pBMD decreases after TKA regardless of the implant material and surgeons must be aware of the complications such as implant loosening and periprosthetic fracture that may occur due to this decrease. Furthermore, according to our study, TiN implants may be considered in osteoporotic patients undergoing TKAs since it may better preserve the bone stock than CoCr implants.

This study has several limitations. The follow-up period was 2 years, which is relatively short to observe the long-term effect of an implant material on pBMD. Therefore, as an ancillary analysis, the authors estimated pBMD using simple radiographs for up to 9 years. Furthermore, cemented TKAs were compared in this study. Thus, different amounts of stress shielding due to different implant materials may have been masked by cement, which lies in-between the implant and the underlying bone. Nonetheless, to our knowledge, this is the only prospective study that compared the pBMD of TKAs performed with two different materials.

The pBMD significantly decreased 2 years after TKA in certain regions regardless of the implant material used. However, the decrease was significantly less with TiN compared to CoCr in specific regions of tibia and femur. Although further studies should be done to validate this hypothesis, stress shielding effect of implant material and TKA implant structure may account for this decrease in certain areas of bone. The TiN implant was beneficial in preserving the peri-implant bone stock after TKA.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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Ju Young Cho (researcher, Seoul National University Hospital) randomly allocated the side of each implant. Seon Wook Kim (technician, Seoul National University Hospital) and Yeon Jin Jung (technician, Seoul National University Hospital) performed the DXA scans.

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REFERENCES

1. Petersen MM, Olsen C, Lauritzen JB, Lund B. Changes in bone mineral density of the distal femur following uncemented total knee arthroplasty. J Arthroplasty. 1995;10(1):7-11.
2. Saari T, Uvehammer J, Carlsson LV, Regner L, Karrholm J. Posterior stabilized component increased femoral bone loss after total knee replacement. 5-year follow-up of 47 knees using dual energy X-ray absorptiometry. Knee. 2006;13(6):435-9.
3. Minoda Y, Ikebuchi M, Kobayashi A, Iwaki H, Inori F, Nakamura H. A cemented mobile-bearing total knee replacement prevents periprosthetic loss of bone mineral density around the femoral component: a matched cohort study. J Bone Joint Surg Br. 2010;92(6):794-8.
4. Jarvenpaa J, Soininvaara T, Kettunen J, Miettinen H, Kroger H. Changes in bone mineral density of the distal femur after total knee arthroplasty: a 7-year DEXA follow-up comparing results between obese and nonobese patients. Knee. 2014;21(1):232-5.
5. Yoon C, Chang MJ, Chang CB, Song MK, Shin JH, Kang SB. Medial tibial periprosthetic bone resorption and its effect on clinical outcomes after total knee arthroplasty: cobalt-chromium vs titanium implants. J Arthroplasty. 2018;33(9):2835-42.
6. Petersen MM, Nielsen PT, Lebech A, Toksvig-Larsen S, Lund B. Preoperative bone mineral density of the proximal tibia and migration of the tibial component after uncemented total knee arthroplasty. J Arthroplasty. 1999;14(1):77-81.
7. Bernatz JT, Krueger DC, Squire MW, Illgen RL 2nd, Binkley NC, Anderson PA. Unrecognized osteoporosis is common in patients with a well-functioning total knee arthroplasty. J Arthroplasty. 2019;34(10):2347-50.
8. Zhang QH, Cossey A, Tong J. Stress shielding in periprosthetic bone following a total knee replacement: effects of implant material, design and alignment. Med Eng Phys. 2016;38(12):1481-8.
9. Martin JR, Watts CD, Levy DL, Kim RH. Medial tibial stress shielding: a limitation of cobalt chromium tibial baseplates. J Arthroplasty. 2017;32(2):558-62.
10. Abu-Rajab RB, Watson WS, Walker B, Roberts J, Gallacher SJ, Meek RM. Peri-prosthetic bone mineral density after total knee arthroplasty: cemented versus cementless fixation. J Bone Joint Surg Br. 2006;88(5):606-13.
11. Trevisan C, Bigoni M, Denti M, Marinoni EC, Ortolani S. Bone assessment after total knee arthroplasty by dual-energy X-ray absorptiometry: analysis protocol and reproducibility. Calcif Tissue Int. 1998;62(4):359-61.
12. Small SR, Ritter MA, Merchun JG, Davis KE, Rogge RD. Changes in tibial bone density measured from standard radiographs in cemented and uncemented total knee replacements after ten years' follow-up. Bone Joint J. 2013;95(7):911-6.
13. Soininvaara TA, Miettinen HJ, Jurvelin JS, Suomalainen OT, Alhava EM, Kroger HP. Periprosthetic femoral bone loss after total knee arthroplasty: 1-year follow-up study of 69 patients. Knee. 2004;11(4):297-302.
14. Ishii Y, Noguchi H, Sato J, Ishii H, Todoroki K, Toyabe SI. Association between body weight and proximal tibial bone mineral density after bilateral total knee arthroplasty. Knee. 2017;24(5):1153-9.
15. Suzuki T, Sukezaki F, Shibuki T, Toyoshima Y, Nagai T, Inagaki K. Teriparatide administration increases periprosthetic bone mineral density after total knee arthroplasty: a prospective study. J Arthroplasty. 2018;33(1):79-85.
16. Buechel FF, Helbig TE, Pappas MJ. 31 Year evolution of the rotating-platform total knee replacment: coping with "Spin-out" and wear. J ASTM Int. 2011;9(2):1-14.
17. Makaram N, Clement ND, Hoo T, Nutton R, Burnett R. Survival of the low contact stress rotating platform total knee replacement is influenced by age: 1058 implants with a minimum follow-up of 10 years. Knee. 2018;25(6):1283-91.
18. Hooper G, Rothwell A, Frampton C. The low contact stress mobile-bearing total knee replacement: a prospective study with a minimum follow-up of ten years. J Bone Joint Surg Br. 2009;91(1):58-63.
19. Regner LR, Carlsson LV, Karrholm JN, Hansson TH, Herberts PG, Swanpalmer J. Bone mineral and migratory pat-

terns in uncemented total knee arthroplasties: a randomized 5-year follow-up study of 38 knees. Acta Orthop Scand. 1999;70(6):603-8.

20. Saari T, Uvehammer J, Carlsson L, Regner L, Karrholm J. Joint area constraint had no influence on bone loss in proximal tibia 5 years after total knee replacement. J Orthop Res. 2007;25(6):798-803.
21. Cameron HU, Cameron G. Stress-relief osteoporosis of the anterior femoral condyles in total knee replacement: a study of 185 patients. Orthop Rev. 1987;16(7):449-56.
22. Mintzer CM, Robertson DD, Rackemann S, Ewald FC, Scott RD, Spector M. Bone loss in the distal anterior femur after total knee arthroplasty. Clin Orthop Relat Res. 1990;(260):135-43.
23. Petersen MM, Lauritzen JB, Pedersen JG, Lund B. Decreased bone density of the distal femur after uncemented knee arthroplasty: a 1-year follow-up of 29 knees. Acta Orthop Scand. 1996;67(4):339-44.
24. van Loon CJ, Oyen WJ, de Waal Malefijt MC, Verdonschot N. Distal femoral bone mineral density after total knee arthroplasty: a comparison with general bone mineral density. Arch Orthop Trauma Surg. 2001;121(5):282-5.
25. Tissakht M, Ahmed AM, Chan KC. Calculated stress-shielding in the distal femur after total knee replacement corresponds to the reported location of bone loss. J Orthop Res. 1996;14(5):778-85.
26. Van Lenthe GH, de Waal Malefijt MC, Huiskes R. Stress shielding after total knee replacement may cause bone resorption in the distal femur. J Bone Joint Surg Br. 1997;79(1):117-22.
27. Soininvaara T, Kroger H, Jurvelin JS, Miettinen H, Suomalainen O, Alhava E. Measurement of bone density around total knee arthroplasty using fan-beam dual energy X-ray absorptiometry. Calcif Tissue Int. 2000;67(3):267-72.