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Measurement of Bone Density Around Total Knee Arthroplasty Using Fan-Beam Dual Energy X-ray Absorptiometry

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Abstract. The clinical survival of joint arthroplasties is clearly associated with the quality of surrounding bone environment. Bone mineral density (BMD) is an important measure of bone strength and quality. Periprosthetic BMD can be measured by using dual-energy X-ray absorptiometry (DXA) with special software algorithms. We studied short-term reproducibility of the periprosthetic BMD measurements after total knee arthroplasty (TKA) in 30 patients with primary osteoarthrosis. The operated knees and the contralateral control knees were measured twice and the results were expressed as a coefficient of variation (CV%). The average precision error was 3.1% in femoral regions of interest (ROI) and 2.9% in tibial ROIs after TKA. In the prosthesis-free control knees, CV% were similar; 3.2% and 2.5%, respectively. The best precision was found in the femoral diaphyses above the implant (1.3%), whereas the least reproducible BMD was determined in the patellar region of the TKA knees (6.9%). Our results confirm that DXA measures precisely small bone mineral changes around TKA and makes it possible to follow bone remodeling DXA and may provide a feasible method for monitoring TKA in the future.

Key words: Knee arthroplasty — BMD — DXA — Reproducibility — Precision.

Traditionally, the results of total knee arthroplasties (TKA) have been evaluated by postoperative clinical status (knee function, stability, range of motion, painfulness) and plain radiographs. Plain radiographs can be used for assessing the position of a prosthesis and the alignment of the knee, for evaluating the bone-prosthesis and bone-cement interfaces, and for providing evidence of infection, loosening, or subsidence. However, the quantitative evaluation of periprosthetic bone density is unreliable in plain radiographs [1–5].

Changes in bone density must exceed 20–40% in order to be visually observable in standard radiographs [2, 5–8]. The computer processing of radiographs enables detection of losses of 8% and more, while dual-energy X-ray absorptiometry (DXA) is able to disclose bone loss below 8% [2, 5]. The recent development of software algorithms has enabled the measurement of bone density adjacent to metal implants [1–3, 6, 9–11].

The functional strain is a well-known determinant of bone remodeling [2, 6–9, 12]. An implantation of TKA alters mechanical loading of both femur and tibia [2, 4, 8, 12]. The loss of bone after TKA in the distal anterior femur is mentioned as a risk factor for supracondylar fractures of the femur [8, 12, 13]. Although periprosthetic fractures are not common after TKA they present a treatment dilemma [12, 13]. Bone loss in the distal anterior femur or under the tibial plate may also lead to loosening of the component and induce difficulties during a revision knee arthroplasty [4, 8, 12, 13].

As the clinical survival of implants is clearly associated with the quality of the surrounding bone environment [2, 4, 10, 11, 14], it is important to investigate periprosthetic bone quality after TKA. In this study, precision of the custom DXA analysis of the distal femora and the proximal tibiae were determined. The data of the present study are essential for prospective studies, in which DXA measurements will be used for characterizing the role of BMD changes in the long-term success of TKA.

Materials and Methods

Patients

The study included 30 patients (11 men, 19 women), mean age 67 years (SD 10.6), with unilateral total knee arthroplasties operated on in Kuopio University Hospital from May 1997 to March 1998. Their mean weight was 78.7 (SD 14.5) kg and mean body mass index was 28.0 (SD 4.4). The prostheses used in the operations were Duracon modular (Howmedica Inc., Rutherford, NJ/ International Division of Pfizer), Nexgen (Zimmer, Warsaw, IN, USA) and AMK (DePuy, Division of Boehringer Mannheim Corporation/DePuy, Warsaw, IN). All prostheses were implanted with bone cement. The prosthesis-free contralateral knee of each patient was used as a control for bone densitometry. We included patients free from any disease or medication known to influence bone

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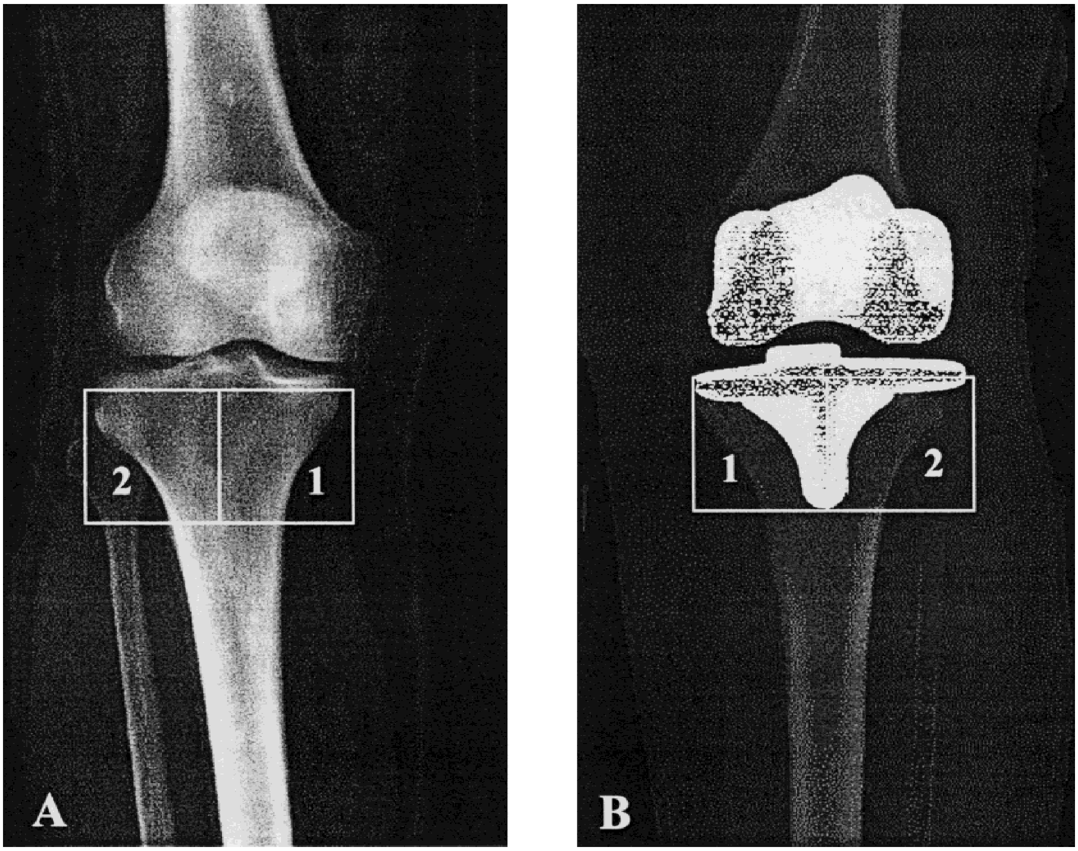

Fig. 1. The location of ROIs in anteroposterior DXA scans. **(A)** unoperated and **(B)** TKA-operated knees. A diaphyseal midline was used to divide the medial (ROI 1) and lateral (ROI 2) ROIs. The fibula was excluded from the analysis manually.

mineral metabolism and who were willing to participate in a 2-year follow-up study. All women had reached their physiological menopause. The patients had osteoarthrosis as an indication for TKA.

Bone Densitometry

Fan-beam dual X-ray absorptiometry (Expert-XL Lunar Corp., Madison, WI, USA) was used for measuring periprosthetic bone mineral density (BMD). The system is equipped with a high-resolution detector array on a rotatable C-arm gantry, coupled to an X-ray tube in a fan-beam geometry. Dual-energy imaging is achieved by filtration of the X-ray beam and the use of detector arrays sensitive to lower and higher energy X-rays [15]. Maximum effective doses are reported to be about 40 μSv for the proximal femur using Expert or Expert XL, when ovaries are outside the primary field [16, 17]. Knee measurements expose even less dose to vital organs, allowing repeated measurements with negligible extra hazard for the patient.

The knee joints of the patients were scanned in both anteroposterior (AP) and lateral projections. For each AP scan the patient lay supine and the leg was strapped into a foot brace in a 15° internal rotation. For the lateral scan, the patient lay on her/his side with the knee flexed at a 15° angle. Prosthesis flanges were used for determining the location of regions of interest (ROIs). Two repeated scans were performed on AP and lateral projections. The patients were repositioned between scans, i.e., each patient was turned to the other side and the contralateral knee was measured in the meantime. Using the forearm software (version 1.63) protocol of the Expert XL, the measurement distance was automatically adjusted. The measurements were performed by four experienced technicians 3–7 days postoperatively.

Bone Mineral Data. Bone mineral density (BMD, g/cm^2), bone mineral content (BMC, g), and area (cm^2) was analyzed using the software algorithm developed by the manufacturer. The algorithm enables bone mineral analysis in the presence of metal in the scanning field. In order to minimize operator-related inaccuracies using manual drawing, no attempt was made to exclude a cement mantle from the analysis. An edge-detection algorithm defines the outlines of bone, soft tissue, air, artifact, and neutral areas. To properly recognize these areas, plastic background was used as recommended by the Lunar Company (personal communication).

Examples of ROI locations are presented in Figures 1 and 2. After locating ROIs manually for the first scan, the "compare" facility of the software was used for copying ROIs for the second scan. The control knees were also analyzed using similar ROIs. In order to guarantee similarity of diaphyseal ROIs 3 and 4, we used equal distances from the joint level in both the operated and the control knees. The distal metaphyseal ROIs of femur were rectangular in shape, with equal width and length as in the operated knees. These ROIs were positioned as mirror images 1 cm below ROI 4. However, due to metallic implant, the area of ROIs 5–8 were smaller in the operated side. The lateral projection ROIs measured mainly femoral BMD, and AP projection ROIs measured tibial BMD, respectively. One experienced operator analyzed all scans.

The number of included knee projections vary because postoperative pain prevented measurement of all four duplicate scans on each patient (Tables 1–4). The number of ROIs 3, 4, and 9 are lower because they were not fully visualized in either of the repeated DXA images and were therefore excluded from this study.

Analysis of precision. The precision of the technique, based on two repeated scans, was calculated as the root mean square (RMS)

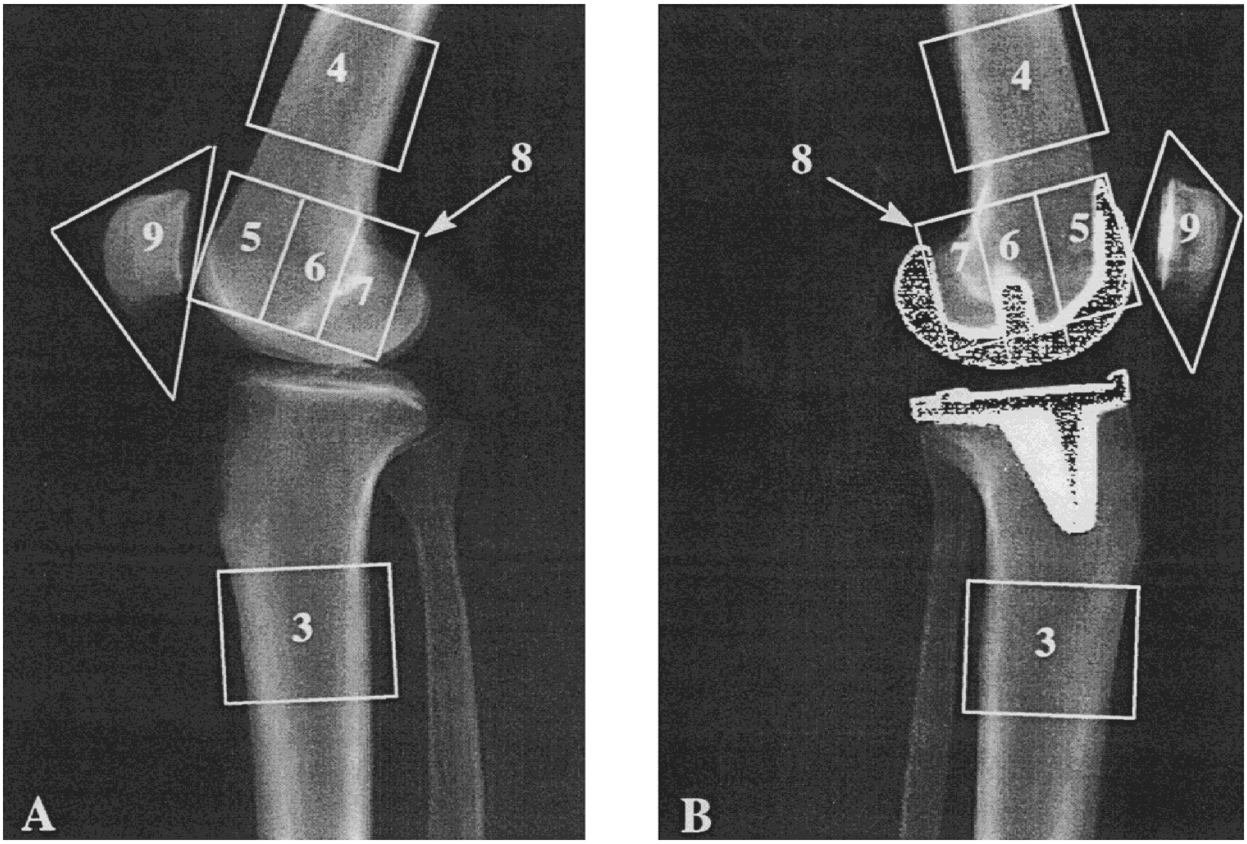

Fig. 2. The location of ROIs in lateral projection DXA scans. **(A)** unoperated and **(B)** TKA-operated knees. ROIs 3 and 4 are diaphyseal. ROIs 5–7 are located distally in the metaphyseal femur. The mid-longitudinal axis of femur was used as a boundary between ROIs 5 and 6. The posterior cortex of femur indicates the boundary between ROIs 6 and 7. The large distal ROI 8 enclosed the area of ROIs 5–7, but was separately measured.

coefficient of variation (CV%) on each projection and patient. This was calculated by using the formula suggested by Glüer [18]:

$$CV\,(\%) = n\,\frac{\sqrt{\dfrac{1}{2n}\displaystyle\sum_{i=1}^{n} d_i^2}}{\displaystyle\sum_{i=1}^{n}\frac{1}{2}\,(x_{1,i}+x_{2,i})}$$

where n is the number of paired observations, d is the difference between two paired measurements, X_1 and X_2.

Results

BMD, BMC, and Area values of the two repeated measurements of the TKA knees and the contralateral unoperated control knees are presented in Tables 1 and 2. The mean periprosthetic BMD precision error (CV%) was 3.1% in femur, 2.9% in tibia, and 6.9% in patella. In the contralateral unoperated knees the BMD precision errors were equally low; 3.2% in femur, 2.5% in tibia, and notably better in patella, 2.0%. Femoral diaphyseal ROIs above the implant (ROI 4) showed the lowest BMD precision errors in both the operated and unoperated knees; 1.3% and 1.7%, respectively (Tables 3, 4).

Discussion

The long survival of modern prosthesis implants poses new threats to their longevity. Stress-shielding phenomena and related concerns, such as marked osteopenia in distal anterior femur, can induce failure of the host bone and thus cause supracondylar periprosthetic fractures or possibly loosening of a component [2, 8, 12, 13]. We were interested in studying periprosthetic TKA bone quality by fan-beam DXA and evaluating the measurement reproducibility for the future longitudinal investigation.

The precision (CV%) of DXA for the determination of BMD in the AP lumbar spine is reported to be within 1.9% [15, 20–22]. For lateral scans, BMD precision varies from 2.0% to 3.7% with fan-beam DXA [20]. Typically, BMD precision of femoral neck ranges from 1% to 5% [15, 21, 22] and that of periprosthetic hip from 1.0% to 7.5% [1–3, 6, 9, 10]. Our precision values for TKA BMD using a fan-beam DXA are similar to those reported after total hip arthroplasty (THA) [2, 6, 9, 10].

Although DXA has increasingly been used for evaluating periprosthetic bone after THA, only a few studies deal with TKA [2, 4, 12]. To the best of our knowledge only Trevisan et al. [11] have studied the reproducibility of DXA with periprosthetic TKA. They report precision error values (BMD CV% 0.9–4.7%) for somewhat larger ROIs than ours, and their results are in close agreement with our study [11].

Three smaller ROIs in the distal femur showed slightly weaker BMD precision (3.2–5.4%) compared with the larger ROI 8, which enclosed the area of all three ROIs (1.9–2.6%). This is consistent with previous findings: the

Table 1. BMD, BMC, and Area values (mean ± SD) at tibial (n = 24), femoral (n = 24), and patellar (n = 15) ROIs of the operated knees

Region of interest		BMD (g/cm^2)	BMC (g)	Area (cm^2)
Tibia				
Medial	ROI 1	1.22 ± 0.18	8.06 ± 2.85	6.49 ± 1.77
Lateral	ROI 2	1.31 ± 0.29	9.90 ± 2.90	7.59 ± 1.79
Diaphysis[b]	ROI 3	1.09 ± 0.23	12.52 ± 3.03	11.10 ± 1.29
Femur				
Diaphysis[c]	ROI 4	1.32 ± 0.24	12.17 ± 2.52	9.12 ± 0.74
Anterior	ROI 5	1.24 ± 0.26	6.00 ± 1.86	4.99 ± 1.13
Central	ROI 6	1.40 ± 0.32	7.96 ± 2.95	5.63 ± 1.30
Posterior	ROI 7	1.69 ± 0.23	7.76 ± 3.48	4.49 ± 1.67
Large distal	ROI 8	1.40 ± 0.24	21.84 ± 7.24	15.19 ± 3.66
Patella				
Patella	ROI 9	1.41 ± 0.25	7.88 ± 1.81	5.50 ± 0.84

[a] For location of ROIs see Figs. 1, 2.
[b] (n = 20)
[c] (n = 22)

Table 2. BMD, BMC and Area values (mean ± SD) at tibial (n = 21), femoral (n = 19), and patellar (n = 16) ROIs of the control knees

Region of interest		BMD (g/cm^2)	BMC (g)	Area (cm^2)
Tibia				
Medial	ROI 1	1.07 ± 0.16	12.96 ± 2.96	12.03 ± 1.96
Lateral	ROI 2	1.07 ± 0.16	14.37 ± 3.22	13.40 ± 2.12
Diaphysis[b]	ROI 3	1.12 ± 0.18	12.41 ± 2.54	11.09 ± 1.52
Femur				
Diaphysis[c]	ROI 4	1.41 ± 0.17	12.81 ± 1.88	9.09 ± 1.09
Anterior	ROI 5	1.25 ± 0.23	9.55 ± 2.94	7.58 ± 1.41
Central	ROI 6	1.42 ± 0.40	10.03 ± 3.62	7.04 ± 1.26
Posterior	ROI 7	1.70 ± 0.30	11.70 ± 3.39	6.87 ± 1.48
Large distal	ROI 8	1.45 ± 0.27	31.89 ± 9.00	21.87 ± 3.91
Patella				
Patella	ROI 9	1.16 ± 0.23	8.60 ± 2.27	7.35 ± 0.98

[a] For location of ROIs see Figs. 1, 2.
[b] (n = 17)
[c] (n = 18)

Table 3. The precision (CV%) of BMD, BMC, and Area variables obtained by tibial measurements of the operated (n = 24) and the control (n = 21) knees

Region of interest		CV% BMD	CV% BMC	CV% Area
Operated knee				
Medial	ROI 1	3.3	5.9	3.8
Lateral	ROI 2	3.0	3.5	2.5
Diaphysis[b]	ROI 3	2.3	2.1	2.2
Mean		2.9	3.8	2.8
Control knee				
Medial	ROI 1	2.4	4.4	3.3
Lateral	ROI 2	2.2	3.2	3.1
Diaphysis[c]	ROI 3	2.9	4.2	4.0
Mean		2.5	3.9	3.5

[a] For the location of ROIs see Figs. 1, 2.
[b] (n = 20)
[c] (n = 17)

smaller the area examined, the greater the intrinsic system variability in evaluating the relevant BMDs [1, 6, 7, 9, 11]. Regarding prospective studies, we found it important to study DXA measurement precision separately in these ROIs.

In addition to the CV%, we also calculated standardized CV% (SCV%) [19]. The parameter takes into account the relative spread (±2 SD) of measured values in the study population and therefore can be used to compare the effective precision of different clinical measurements. Our SCV% for BMD measurements ranged from 1.8% (diaphysis, operated knee) to 9.7% (patella, operated knee) and the mean value was 4.5%. From the CV% values given by the manufacturer for BMD in the lumbar spine, femoral neck and radial shaft, Foldes et al. [19] calculated SCV% of 1.46–4.39. Our values are comparable with their CV% and SCV% values.

Apart from ROI size, numerous other factors affect the reproducibility of BMD measurement, including the shape of ROI, complicated configuration of knee joint, variations

Table 4. The precision (CV%) of BMD, BMC and Area variables obtained by femoral and patellar measurements of the operated (n = 24) and the control (n = 19) knees

Region of interest		CV% BMD	CV% BMC	CV% Area
Operated knee				
Diaphysis[b]	ROI 4	1.3	1.6	1.6
Anterior	ROI 5	3.7	7.7	5.0
Central	ROI 6	4.1	5.7	3.7
Posterior	ROI 7	3.8	9.2	7.7
Large distal	ROI 8	2.6	5.0	3.7
Mean		3.1	5.8	4.3
Patella[c]	ROI 9	6.9	1.9	6.9
Control knee				
Diaphysis[d]	ROI 4	1.7	1.6	1.3
Anterior	ROI 5	3.2	4.4	3.8
Central	ROI 6	5.4	6.8	4.2
Posterior	ROI 7	4.0	6.1	6.0
Large distal	ROI 8	1.9	2.4	1.9
Mean		3.2	4.3	3.4
Patella[e]	ROI 9	2.0	1.9	3.2

[a] For the location of ROIs see Figs. 1, 2.
[b] (n = 22)
[c] (n = 15)
[d] (n = 18)
[e] (n = 16)

in prosthesis size and design, amount of cement around the prostheses, knee positioning, bone heterogeneity, and operator consistency [2, 6, 9, 21]. Patient positioning probably causes the most differences and variations in the repeated measurements [1–3, 6, 9, 22].

Differences in the precision between ROIs can partly result from the variation in distribution and amounts of cortical and cancellous bone among regions [6], caused by both the shape of a knee joint and a prosthesis. A slight rotational change in position causes a prosthesis flange to shadow either patella or distal femoral bone and diminish reproducibility of lateral projections. Similarly, a tibial stem can cause rotational problems in AP scans. This was notable in the patella measurements where CV% was worse with the prostheses (6.9%) compared with the control knees (2.0%). The cement fixation and the plastic implant also shadow the patella. The weaker precision may also be due to the size variation of patellae. The lowest precision errors (of BMD) were found in the femoral and tibial diaphyseal ROIs: 1.3% and 2.3% in the TKA knees and 1.7% and 2.9% in the control knees, respectively. Precision was excellent in these ROIs because rotation causes negligible changes in ROI area size, and no effects of surgery should be expected. The reproducibility of DXA scans on the TKA-free side was similar in femur and even better in proximal tibia than that obtained in the operated knees.

All the patients underwent total knee arthroplasty where cemented implants were used. In order to minimize operator-dependent variability, no attempt was made to exclude the thin cement layer needed in the primary TKAs from BMD and BMC calculations. To limit the cement mantle and positioning effects, each knee is used as its own reference, and TKA knees and TKA-free knees are taken as separate study groups.

Since the fan-beam geometry shows a linear magnification effect, the area and BMC values of bone are slightly dependent on the measurement height-off-the-table. However, BMD is not dependent on height-off-the-table and it can be used as a fundamental variable in assessing bone density. Eiken et al. [23] found that area and BMC were increased by 2.8%/cm decreased distance as BMD remained unaffected with the use of a QDR-2000 fan-beam system.

The choice of measurement areas made it possible to determine the precision of the regions that are supposed to reveal stress-shielding changes after TKA and to offer better understanding of knee alignment responses to BMD. The location of ROIs is based on reference points on the prosthetic implants, which helps to define ROI limits and enables the usage of "compare" facility. However, the "compare software" improves precision errors by allowing more detailed repositioning of ROIs. The reproducible positioning of these ROIs is essential with longitudinal investigation [1, 2, 3, 6, 10, 20].

The prevalence of bone loss and its relationship to prosthetic performance remain unknown because traditional plain radiographs as the correspondence between radiographic and histological or clinical findings has often been disappointing and there is an absence of interobserver agreement of radiographic outcomes. Some authors have measured up to 36–44% decreases of BMD after TKA [4, 12]. In our study, precision error was much smaller than expected BMD changes. Our results show that DXA is not only a suitable method for monitoring BMD around hip prostheses, but a high-resolution DXA is suitable for monitoring BMD around knee prostheses.

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