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Measurement of bone mineral density is possible with standard radiographs

A study involving total knee replacement

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Background Measured bone density correlates well with the mechanical properties of the bone. Our objective was to evaluate optical densitometry as a method of measuring the periprosthetic bone density of the tibial platform in total knee replacement using serial dual-energy X-ray absorptiometry (DXA) as the reference test.

Methods 30 patients who underwent a cemented total knee replacement were followed up for over 2 years. Standard radiographs of the knee were obtained at 12 and 24 months. These were photographed with a digital camera and enhanced with image processing software. A DXA scan was performed at the same time as the reference method. 3 regions of interest were defined under the tibial plateau (medial, lateral and stem positions).

Results After 24 months of follow-up there was a significant decrease in density in the 3 regions, both with the optical and DXA methods. The concordance between methods was studied using Bland and Altman plots, Cronbach's alpha and intraclass correlation coefficients resulted in values from 0.72 to 0.87, depending on the region and the follow-up time.

Interpretation Quantification of optical density values with a standardized measurement system on conventional radiographs is a reliable and efficient method of determining the bone mineral density.

Failures of total knee replacement (TKR) are more common on the tibial side and they are related to alignment errors, with an unstable fixation or with a decrease in bone quality near the prosthesis (Li et al. 2000). The mineral density of trabecular bone is directly related to the mechanical properties and the quality of the bone; thus, the mechanical properties of the trabecular bone in the proximal part of the tibia are considered to be an important predictor of TKR failure.

Visual examination of radiographs is not sufficiently accurate to allow evaluation of bone loss, and it does not provide any way of quantifying that loss with the passage of time. Radiographs only reveal a large degree of reduction in bone mineral density (BMD), while the conventional densitometric study permits quantification of the bone loss (Robertson et al. 1994). Serial dual-energy X-ray absorptiometry (DXA) scans cannot be used in many locations due to absence of the necessary infrastructure, and also due to the high cost of this technique.

We assessed whether a digital radiographic image acquisition and processing system might be used to replace the conventional densitometry method in measurement of bone mineral density in the periprosthetic tibial region of TKRs.

Patients and methods

At our department, 169 patients underwent TKR in 1999 and 2000. We took a random sample of 30 patients and evaluated 29 of them (20 women) because 1 of the sampled patients could not be contacted at the 24-month follow-up. Inclusion criteria were normal clinical and radiographic outcome, and no complications. None of the patients was given medication for osteoporosis. The mean age was 70 (58–86) years. In all patients, the implanted prosthesis was Interax (Stryker Howmedica Osteonics, Allendale, NJ), with cruciate retention. It had a cylindrical tibial stem 35 mm in length and all-cemented components. The study was approved by the Regional Ethics Committee.

All study subjects had a standard anteroposterior radiograph taken 12 and 24 months after surgery, using Philips Optimus equipment (Royal Philips Electronics, the Netherlands). The radiograph was taken following a previously established protocol: adjustment to 52 kV/s and 10 mA, focus-film distance 1 m, patients positioned at 180° knee extension using a splinting shank to avoid (or at least minimize) artefactual movements so that we could obtain reproducible data. Fluoroscopy was used to ensure correct adjustment to the anteroposterior plane. A vitallium reference (the same chrome, cobalt and molybdenum alloy as the prosthesis) was placed onto the skin of the knee to ensure that the density of the prosthesis matched the reference density.

The radiographs were photographed with a Canon Powershot 600 digital camera (Canon US Inc., NY) with a 570,000-pixel CCD (832 × 608 pixel spatial resolution; CCD size: 4.8 inch × 3.6 inch), fixed focal length 50 mm, Iso rating 100 and maximum aperture f2.5. The images were captured in a 256-level gray scale using the RAW format (no compression). The digital image analysis was performed on a PC using the public domain ImageJ program for Windows (developed at the U.S. National Institutes of Health and available at <http://rsb.info.nih.gov/ij>).

We defined three regions of interest (ROIs) of 1 cm² area, each one located under the tibial component and coincident with Ewald's (1989) zones 2, 3 and 6: ROI-1 at the medial position, ROI-2 at the lateral position, and ROI-3 at the stem position.

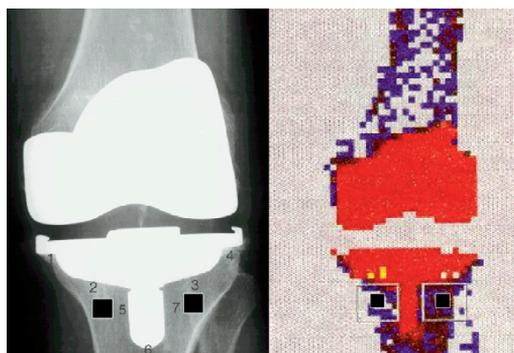


Figure 1. Definition of ROI-1 and ROI-2 in radiographs and DXA scans.

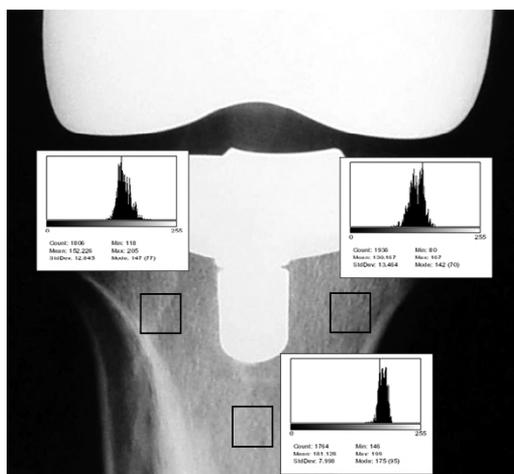


Figure 2. ROIs and density measurement by the optical method.

ROI-1 and ROI-2 were situated 1 cm underneath the tibial plateau and 1 cm from the external and internal border of the stem, respectively (Figure 1). ROI-3 was localized 1 cm below the end of the central stem. First of all, a histogram of equalization was made to ensure standardization of the gray-scale levels using the metal density and the air density as the maximum and minimum density references (Figure 2). The optical density was measured in the defined ROI over a 0–255 gray scale.

At the same time that the radiographic examination was done, we performed DXA scans of the knees with a Norland XR 26 MARK II™ system (Cooper Surgical, Inc., Trumbull, CT). The mean density of the previously defined ROI was determined in g/cm² units. For each patient, we calculated two mean density values—both for the opti-

Table 1. Mean of density in the three ROIs at 12 and 24 months, and relationship regarding gender of patients

Technique	Follow-up (months)	Sex	Mean	SD	P-value ^a
DXA	12	Men	0.96	0.11	0.002
		Women	0.84	0.075	
	24	Men	0.93	0.096	
		Women	0.81	0.069	
Radiographs	12	Men	147	15	0.005
		Women	128	9.22	
	24	Men	137	14	
		Women	123	12	

^a Mann-Whitney U-test

cal values and for the DXA values. One of them (M3) averaged the three ROIs, while the other (M2) averaged only ROI-1 and ROI-2. This was done because the periprosthetic bone near the stem (ROI-3) is affected by mechanical forces differently in comparison to the other regions.

Statistics

We used Kolmogorov-Smirnoff Normality adjustment tests for continuous variables. Parametric or nonparametric tests were used, depending on the distribution of variables. We used Student's t-test or the Mann-Whitney test to test continuous or ordinal variables within two groups. We used Chi-square test or Fisher's exact test for categorical or dichotomous variables.

We performed a reliability analysis to assess the concordance between optical and densitometry measurements. Both scales were standardized to compensate for the different units of measurement (g/cm^2 vs. gray-scale level), thus giving Z-scores for M2 and M3 values both for the 12 months and 24 months. The consistency was calculated by Cronbach's alpha and intraclass correlation coefficient (fixed effects model), and graphically represented with Bland and Altman (1986) plots. We also performed a linear regression analysis to obtain a prediction model where we could estimate the DXA value from the optical densitometry value. P-values less than 0.05 were considered to be statistically significant. Statistical calculations and plots were done with SPSS version 11 (SPSS

Table 2. Density obtained in the three ROIs, and average at 12 and 24 months

Technique	ROI	12 months Mean	12 months SD	24 months Mean	24 months SD	P-value ^a
DXA	1	0.88	0.12	0.85	0.12	0.003
	2	0.78	0.14	0.77	0.12	0.04
	3	0.97	0.09	0.92	0.09	< 0.001
	M2	0.83	0.12	0.81	0.11	< 0.001
	M3	0.88	0.10	0.84	0.09	< 0.001
	Radiographs					
	1	136	17	127	18	< 0.001
	2	114	20	112	22	< 0.001
	3	152	14	143	14	< 0.001
	M2	125	16	120	17	< 0.001
	M3	134	14	127	14	< 0.001

^a Wilcoxon test

Inc., whereabouts) and Medcalc version 7.4.3.1 (supplier, whereabouts) for Windows.

Results

The M3 values (density average of the three ROIs) were higher in men, both at 12 and at 24 months and using both measurement methods (Table 1). We found a decrease in density from 12 to 24 months in the three ROIs individually, and also in the averaged M2 and M3. This reduction in density was statistically significant in all the ROIs and for both methods (Table 2).

The consistency between DXA and the optical method calculated with Cronbach's alpha was 0.93 at 12 months and 0.86 at 24 months for M2 values, and 0.92 (12 months) and 0.84 (24 months) for M3 values. The intraclass correlation coefficient between both methods was 0.88 and 0.85 for M2 and M3 values, respectively, at 12 months and 0.76 and 0.72 for M2 and M3 values, respectively, at 24 months. All differences were significant at the $p < 0.001$ level. Bland and Altman plots within the 1.96 SD limits (Figure 3) confirmed a high concordance between the two measurement methods. We calculated linear regression models for each of the ROIs and the M2 and M3 averages to predict the value of the DXA value from the value of the optical density (at 24 months: $y = 0.2058 + 0.005 \times$ for M2, and $y = 0.2172 + 0.0049 \times$ for M3) (DXA value prediction (y) from radiographic values (x)).

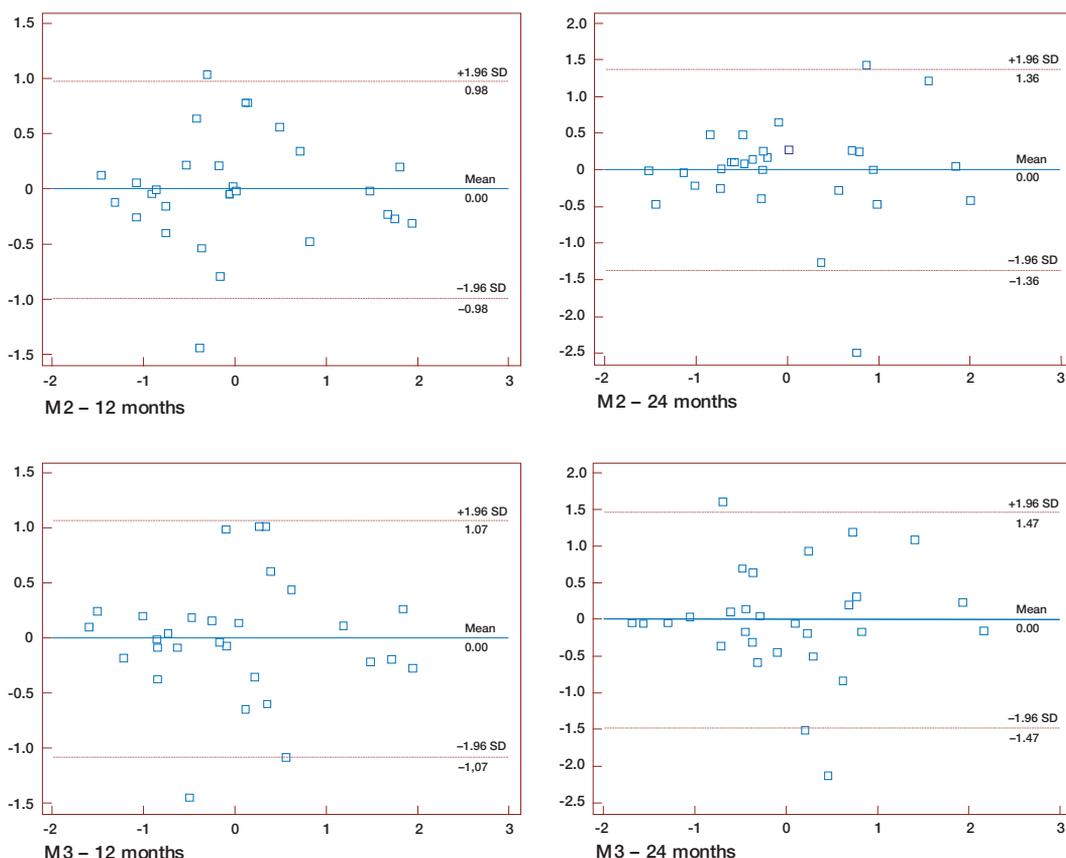


Figure 3. Bland and Altman plots for M2 and M3 at 12 and 24 months. Average of DXA (g/cm^2) and optical density (gray-scale value) is shown on the horizontal axis. DXA (g/cm^2) – optical density (gray-scale value) is shown on the vertical axis.

Discussion

A reduction in bone mineral density is an early sign of alteration in the mechanical limb axis or implant migration. A reduction of BMD in the supportive areas of the prosthesis can cause subsidence of some components, especially of the tibial plateau. The conventional radiographs do not have enough sensitivity to allow diagnosis of the bone loss, and do not allow quantification. Several studies have shown that a loss of 30–50% of bone must occur before a change is detectable visually (Mirsky and Einhorn 1998).

Different quantitative methods for determination of BMD have been developed. Although it cannot discriminate between trabecular and cortical bone, the DXA seems to be the most accurate method, combining high precision and low radia-

tion dose. There have been many studies confirming the usefulness of DXA for monitoring implant stability (Trevisan et al. 1998), early measurement of changes in periprosthetic density, and bone reaction after an arthroplasty (Cohen and Rushton 1995, Karbowski et al. 1999, Ishii et al. 2000, Mirsky et al. 2001). Many studies (Lonner et al. 2001, Van Loon et al. 2001) have demonstrated a change, especially a decrease, in the BMD after TKR. DXA scan is an expensive method, however, which is not available in many hospitals with limited resources.

We thus determined whether optical densitometry (measured from standard radiographs) could be used as an alternative to DXA. Digital image analysis systems are up to 20 times more accurate than the human eye (Bould et al. 1999) and improve the accuracy and reproducibility of radio-

graphic measurements. Many articles recommend it for analysis of radiographs after surgery (Pedersen et al. 1998, Kolbeck et al. 1999, Holdsworth et al. 2000). In our study, the digital image is acquired from the X-ray film with a digital camera. A digital image processing software is used. In proper digital radiology, the image sensor is a digital device so the images are digital throughout; therefore, it is not necessary to convert anything to digital form. However, this system is rather expensive and not available in many health centers. The main aim of our work was neither to measure bone density nor to study densitometric changes in the regions near the TKR, but to determine whether optical densitometry could substitute for DXA analysis.

We found that both methods can demonstrate a reduction in BMD from 12 to 24 months in all ROIs. These observations are in accordance with one study in the literature (Levitz et al. 1995). We observed lower density values with the two measurement methods in the three ROIs for women, both at 12 and at 24 months of follow-up. This finding can be related to the higher prevalence of osteoporosis in the female population; however, it does not agree with another study which did not show any differences related to gender (Petersen et al. 1995).

The intraclass correlation coefficients and Cronbach's alpha showed good concordance between both density measurement methods. The optical density measurement allows estimation of the DXA values; thus, knowing the optical density value and using the regression model, we could calculate a densitometry value near to the one obtained with DXA.

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