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Precision of dual energy X-ray absorptiometry in determining periprosthetic bone mineral density of the hydroxyapatite coated hip prosthesis

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ABSTRACT: The objectives of this study were to demonstrate the potential usefulness of dual-energy X-ray absorptiometry (DEXA) in the assessment of dynamic changes in bone mineral density (BMD) around the femoral stem of non cemented hydroxyapatite-coated hip prostheses and to establish our procedures by determining the variabilities associated with error introduced by the machine, operator, and/or subject.
Methods: *Regional BMD were measured twice by DEXA for 27 patients. All scans were analysed twice by applying large size regions of interest (ROI's), 7 in total, defined by 'modified' Gruen zones. The data of 27 patients were analysed for the second time using smaller size ROI's, 14 in total, 7 small ROI's on each of the medial and lateral sides of the prosthesis. Three patients, all of whom exhibited intense ectopic ossification, were scanned twice. The variation associated with rotation of the femur was assessed by scanning six patients first in neutral rotation, thereafter by ± 15° in internal and external rotation position.*
Results: *The overall coefficient of variation (CV) using 'modified' Gruen zones was 2.40% and varied according to the zone assessed. When smaller zones were used, the overall CV was 3.42%. The overall CV in the patients with ectopic ossification was 7.56%. When the leg was rotated by ± 15° externally or internally, the overall CV was approximately 10%.*
Conclusions: *Patient positioning is probably the most variable condition in the clinical setting. Using large ROI's such as 'modified' Gruen zones yields significantly better overall precision than using smaller ROI's. Patients with intense ectopic ossification are not suitable candidates for longitudinal study. (Hip International 2000; 10: 83-90)*

KEY WORDS: Hydroxyapatite, Total hip arthroplasty, Dual-energy x-ray absorptiometry

INTRODUCTION

Bone densitometry technique has undergone rapid changes over the last decade, with markedly improved image resolution, short scan times, exceptionally low radiation dose to patients and inherent stability of calibration (1). Normal changes of mineral content of skeletal tissue proceed at a relatively slow pace ranging from 0.5-2 % per annum for most of the adult life span in healthy individuals to 2-5 % in early postmenopausal women. The reported reproducibility measurements of DEXA of spine and femoral neck are ± 1 % and ± 1.5 % respectively (2). For these reasons DEXA has achieved an unquestioned role in clinical decision making in the management of osteoporotic patients, by monitoring the progression of the disease or the efficacy of the treatment.

Use of the DEXA technique to measure the peripros-

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thetic bone loss and regional bone turnover in cementless total hip arthroplasty (THA) has been studied on numerous occasions (3-10). The *in vitro* measurements of error performed on an anthropomorphic spine phantom, and on prostheses implanted in cadaveric femora, for studying the effects of rotation on precision were well documented by Kiratli et al (5) and Cohen et al (9). However, the effect of rotation on precision *in vivo* has not been adequately determined. Also, using a small size and only a limited number of ROI's was an obvlous limitation of the application of the DEXA technique by Richmond et al (3), Mc Carthy et al (4) and Kiratli et al (5).

The assessment of dynamic changes in BMD around the femoral stem depends on the prosthesic design (6, 11, 12), because different prostheses have different remodelling patterns. Such longitudinal studies depend on the reproducibility of these measurements. Accordingly, all factors that influence the precision of DEXA should be fully recognized. They include the instrument (hardware and/or software), the operator (subject choice of sizes and the numbers of ROI's and placement and determination of the reference point), and the patients (variation in positioning and the effect of heterotopic ossification). Our aims in this cross-sectional DEXA study of patients with unilateral cementless hydroxy apatite-coated hip prostheses were to address the factors affecting the reproducibility of the BMD measurements around the femoral implant if optimum precision is to be achieved, and to establish a protocol for subject positioning and choosing consistent and precise ROI's for imaging analysis during sequential measurements.

METHODS

In Vitro *Measurements*

Bone mineral measurements were performed with a Hologic QDR-2000 plus X-ray bone densitometer (Hologic Inc., Waltham, MA, USA). This machine uses the Kilovolt-switching Technique to give alternating generator potentials of 70 and 140 KVp with effective energies of 43 and 110 KeV respectively. A rotating filter wheel containing bone and soft tissue equivalent sectors calibrates the scan image pixel by pixel and corrects for the effects of beam hardening. (13). *In vitro* precision was measured on the anthropomorphic spine phantom supplied by the manufacturer with prespecified densities. All scans were done in both pencil and fan-beam modes. For the short-term precision, the spine phantom was scanned twenty times in one session. For the long-term precision, daily spine phantom measurements were performed as a part of routine quality control (QC) assurance for the machine. The global ROI size utilized remained unchanged from day to day. The results of the scans were routinely inspected, then entered to the QC database provided. A linear regression of the data was then plotted with manufacturer- provided software and entered into the QC graph.

In Vivo *Measurements*

Thirty three patients with unilateral non-cemented hydroxyapatite (HA)-coated total hip prostheses were invited to participate in the study, which was approved by the Medical Ethics Committee of the hospital. Written informed consent was obtained from all patients. The prostheses used were the Anatomic Benoist Girard (ABG) implant (Howmedica International, Staines, England). The hemispherical metal-backed cup was covered with HA, as was the proximal one third of the stem. An anteroposterior scan of the operated proximal femur was performed in all subjects. The patient was positioned supine on the scan table with the leg in neutral rotation. The knee was placed in a foam positioning device to reduce knee and back discomfort. The foot was strapped into a foot brace with the toes pointing upwards. In this position the femur is parallel to the long axis of the table, and the transverse beam is perpendicular to the femoral shaft. The scan mode used was the pencil beam, as its high resolution provides the best results. Special hip prosthesis software (version 6.1), designed to perform bone-mineral analysis in the presence of metal in the scanning field, was used, because metal completely attenuates the photon beam, and therefore bone lying immediately anterior or posterior to a metal object in the scan path will be obscured; bone which is adjacent medial and lateral to the metal will be measured. The scan time was approximately 10 minutes and the

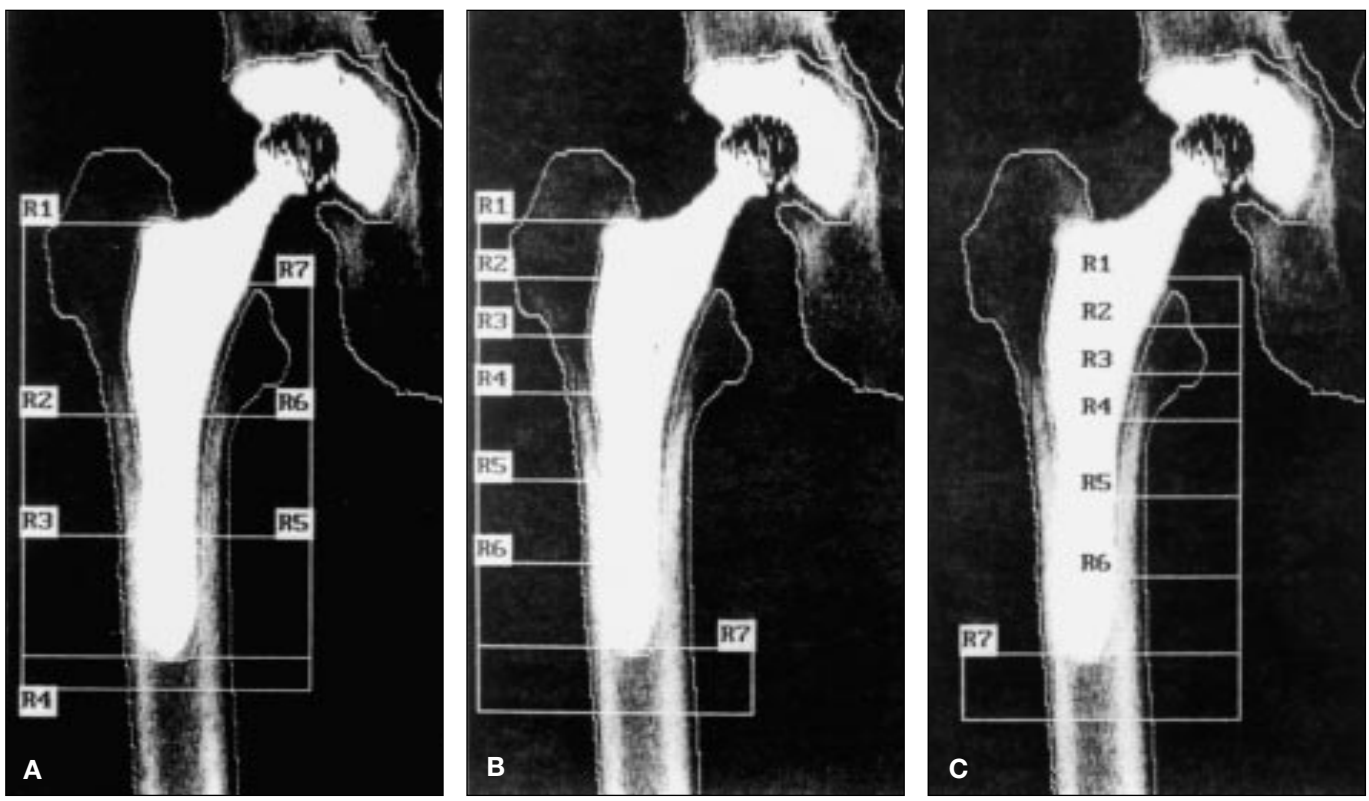

Fig. 1 - (A) *The DEXA scan image using 7 'modified' Gruen zones. The ROI number places proximal to the measured box.* **(B and C)** *DEXA scan images using 14 smaller ROI's: 7 ROI's on each side of the prosthesis. The ROI number placed proximal to the measured box*

skin dose was 6 mrem. The scan parameters used throughout the study were: point resolution 0.1125 cm, line spacing 0.0559 cm, scan length 21.62 cm and width 11.5 cm. And the pixel size was adjustable from 0.5 to 1.1 mm. The "compare" feature of the software was used to create the ROI's based on a template, and it was then manually adjusted to account for the anatomy of each individual. The operator specified seven zones as proposed by Gruen et al (14), which have been widely accepted for the radiological evaluation of THA's. The "compare" mode was used to transfer the ROI's from the baseline scan to the second scan of the same individual. The amount of bone in the beam path is calculated as bone mineral content (BMC) in grams. BMC is then divided by the projected area of the region scanned, and this is reported as BMD in g/cm^2. The written protocol has to be adhered to strictly by all operators for patient positioning and scan analysis, and care must be taken that the integrated area of a repeat scan is identical to the previous one. In order to address the factors affecting precision error, patients were divided into three subgroups.

Subgroup 1.: This group consisted of 27 patients who had experienced a pain-free and uncomplicated functional recovery. They were enrolled in a short-term precision study using DEXA by duplicate measurement. The patients were repositioned between scans. To evaluate the variation associated with different sizes and numbers of ROI's the data of this group were analysed twice: first, by using the 7 'modified' Gruen ROI's, where ROI's number 1 and 7 correspond to the length of the coated area (Fig. 1 A), second, by using 14 smaller ROI's: 7 ROI's on each side of the prosthesis (Figs. 1 B and C). The reference locations for placing the ROI's were the proximal, lateral and medial edges of the implant. The zones 1, 2 and 3 represented the HA-coated regions and 4, 5 and 6 represented the uncoated regions. ROI 7 with heights equal to 20 pixels was placed distal to the tip

of the prosthesis and represented the BMD in g/cm^2 directly distal to the tip.

Subgroup 2.: This group consisted of 3 patients, all of whom exhibited intense ectopic ossification (Brooker grades 3 and 4) (15) and they were scanned twice with repositioning between scans, in order to address the possible variation on the precision measurement of this complication.

Suburoup 3.: This group consisted of 6 patients who had undergone THA without problems. In order to measure the error induced by leg positioning and rotation, 6 implants were scanned first in neutral rotation, and thereafter the leg concerned was rotated internally by ± 15° and the second scan was performed. A third scan was performed with the leg rotated ± 15° externally from the neutral position.

Statistical Analysis

Precision errors were expressed as coefficients of variation (CV), along the lines explained by Glüer et al (2). For each ROI a one-way ANOVA was performed using the patient's identification number as the factor. The root mean square was calculated and divided by the overall mean to obtain CVs for each region using the formula $CV_{sd} = (SD/\sum x_j/m)^* 100\%$, where m = 27 (the sample size of the main part of our study) and the subscript j indicates each patient (2). An F-test was used to test whether the use of the 7 Gruen zones led to statistically significant ($p<0.05$) different precision than the use of the 14 small zones. All calculations were performed with the SPSS statistical package, release 7.5.

RESULTS

In Vitro *Measurements*

For the short-term precision, there were 20 measurements on the spine phantom in one session. The mean CV for the BMD using both pencil and fan-beam modes were 0.39% and 0.40% respectively. For the long-term precision, there were 429 measurements on the spine phantom performed daily between November 1996 and December 1997 as part of routine QC assurance for the machine and covered most of the study period. The pre-specified BMD were 1.0051 g/cm^2 and 1.0064 g/cm^2 using both pencil and fan-beam modes; the calculated mean BMD values were 1.0063 g/cm^2 and 1.0067 g/cm^2; with corresponding CV of 0.41 % and 0.43% respectively.

In Vivo *Measurements*

Subgroup 1: Table I shows the reproducibility of the measurements (as calculated in terms of CV of pair measures) performed in 27 patients on the same day for each of seven Gruen zones. The results for each of the 14 small ROI's are listed in Table II. The average precision error varied according to the zone assessed and ranged from 1.38% in Gruen zone 6 to 4.09% in the small calcar zone (zone 7). The overall CV was 2.40%. When 14 small zones were used, the CV ranged from 1.48% in ROI 7 lateral to 5.24% ROI 2 medial. The overall CV was 3.42% (Tab. II). The use of Gruen zones led to a statistically significant improvement of the overall precision (CV's 2.40% versus 3.42%; $p = 0.006$).

Subgroup 2: In this group, all of whom exhibited intense ectopic ossification, the overall CV was 7.56%.

Subgroup 3: When the leg was internally rotated ±15° the CV ranged from 1.35% in ROI 4 to 19.29% in ROI 7 and the overall CV was 9.58%. When the leg was externally rotated the CV ranged from 2.46% in ROI 4 to 19.80% in ROI 7 and the overall CV was 9.61% (Tab. III). The largest differences in BMD compared with neutral rotation were found in region 7, the calcar and the lesser trochanter (Fig. 2).

DISCUSSION

Accuracy and Precision

In general, small errors of accuracy are of little clinical significance, provided they remain constant. Precision errors reflect the reproducibility of a diagnostic technique, and in practice often have greater clinical relevance than accuracy errors. An understanding of the precision error is useful for two reasons. Firstly results are usually interpreted in the context of the relevant normal range, and a technique with poor precision may lead to misinterpre-

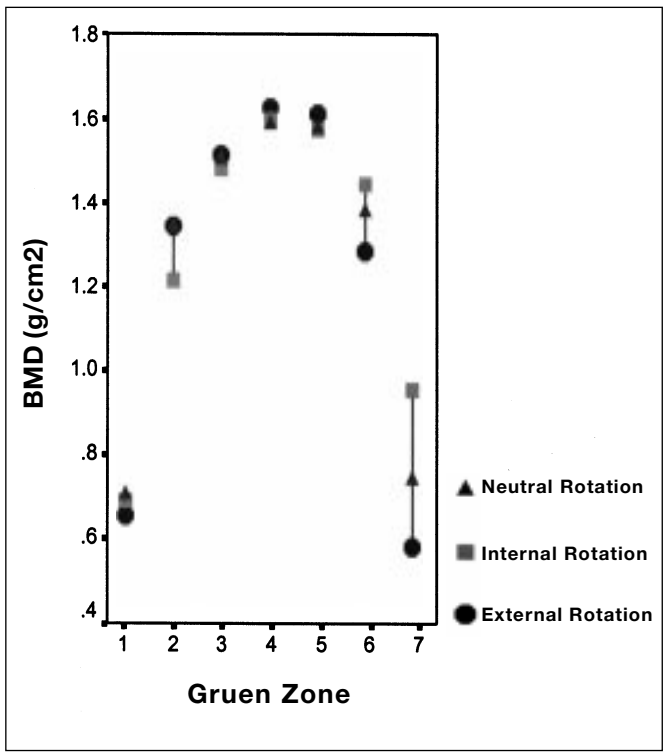

Fig. 2 - *The effect of internal and external rotation on BMDs in 6 patients*

tation of results. Secondly, it is frequently necessary to decide whether a follow up scan provides evidence of a significant change and this can only be decided with knowledge of the precision errors of the technique (16). The minimum detectable significant (5% level) difference between two measurements in a single subject is 2.8% if the precision error is 1%, and 14% if the precision error is 5%. A bone loss of 3% per year, which is the average normal bone loss in the early post menopause, would therefore take one year to detect with a 1 % precision error and 4.7 years with a 5% precision error (17).

In Vitro *Measurements*

Precision on phantoms should always be better than that achieved on patients, as changes due to positioning of patients by the operator and the changes caused by the shapes and sizes of the bones at each site are eliminated. The CV of the spine phantom scans should be of the order of 0.5% or less (18). A CV outside this range is often the result of a vari-

TABLE I - DEXA PRECISION ERRORS (AS CV%) OF BMD USING 7 'MODIFIED' GRUEN ZONES IN 27 PATIENTS

Gruen zone	CV%
1	1.95
2	2.37
3	2.22
4	1.57
5	2.22
6	1.38
7	4.09
Overall	2.40

TABLE II - DEXA PRECISION ERRORS (AS CV%) OF BMD USING 14 SMALL ROI'S IN 27 PATIENTS

14 small ROI's	Lateral (CV%)	Medial (CV%)
1	2.42	5.12
2	4.26	5.24
3	5.03	4.76
4	2.71	2.03
5	2.50	2.02
6	2.67	2.06
7	1.48	1.79
Overall	3.21	3.62

CV for all 14 ROI's is 3.42%

TABLE III - DEXA PRECISION ERRORS (AS CV%) OF BMD USING 7 'MODIFIED' GRUEN ZONES IN 6 PATIENTS WHEN THE LEG WAS ROTATED BY ± 15° EXTERNALLY AND INTERNALLY

Gruen zones	Internal rotation (CV%)	External rotation (CV%)
1	6.44	6.66
2	1 1.66	6.85
3	7.29	4.43
4	1.35	2.46
5	3.67	8.34
6	5.03	8.22
7	19.29	19.80
Overall	9.58	9.61

ation in analysis of scanning procedure. If the CV is greater than 0.7%, and the phantom scans have been properly acquired and analysed, system stability is questionable. Maintenance personnel should be notified and the problem corrected (18). The results of both *in vitro* short-term and long-term measurements showed a very good precision, which indicated a high performance of the DEXA machine and enhanced our ability to estimate true bone changes.

In Vivo *Measurements*

Using proper QC, reproducible and careful subject positioning and more objective image analysis have led to a potential improvement in overall precision (CV = 2.40%). The results showed an extremely high reproducibility for DEXA measurements of periprosthetic BMD. The precision error was 1.38% to 2.37%, except for the small calcar zone (zone 7) with 4.09%.

Effect of the Size and Numbers of the ROI's

Similar studies have been published by Richmond et al, McCarthy et al and Kiratly et al (3-5) using only four small ROI's in the proximal part of the periprosthetic bone. In the study (6) published by Kilgus et al, 6 small ROI's on both the medial and the lateral sides of the metal implants were used, with a reference baseline zone at the diaphyseal bone adjucent to the most distal 5 cm of the femoral implant. The overall CV was 3.8% (2.6-4.7). These authors all used ROI's that were small. When smaller pixel sampling is analysed, fewer photons are collected, quantum statistical variations are greater and measurement precision is consequently degraded (19). Moreover, Kiratli et al experienced difficulty in the reproducibility of small ROI's placement (5). In the analysis protocol in the present study, the BMD was evaluated around the whole femoral implant using seven regions as proposed by Gruen and the results showed significant improvement in the overall precision (2.40% versus 3.42%). We agree with Kilgus et al (6) that, defining the ROI's in relation to part of the implant, is the most reproducible method of localising identical ROI's with repeated studies on the same patient.

The Effect of Positioning

The precision of DEXA measurements of the proximal femur with casual positioning of the foot or leg appears to be of the order of 2-5%, which is inadequate for most longitudinal studies. In comparison, the precision of the DEXA with careful repositioning is about 1% for the femoral neck and trochanter in normal subjects (17). Rotation of the femur about its longitudinal axis altered the BMD measurements significantly. Kiratli et al (5), in a rotation study of implanted cadaver femora, showed that changes in position may influence BMD measurements (2-5% error), but our results on 6 patients showed that measurement precision was extremely sensitive to small changes in rotation. ± 15° internal or external rotation of the femur about its longitudinal axis caused 9.58% and 9.61% differences compared with neutral rotation. This agrees with the data published by Cohen et al (9) using two implanted cadaver femora.

Before the patient leaves the table the scan produced should always be carefully inspected, because any slight movement will have caused image disturbance (Figs. 3 A and B).

Effect of Ectopic Ossification

Ectopic ossification is a frequent complication with varying degrees of intensity (13). The BMD measurements could be elevated because of the presence of heterotopic ossification (20). Kilgus et al (6) have observed high variations in BMD in repeated scans of regions where the bone density is very irregular, as in areas of heterotopic bone. In our study patients with intense ectopic ossification had a high precision error (CV = 7.56%).

CONCLUSIONS

- DEXA is a very sensitive and reproducible method for detection of even small density changes of periprosthetic bone, provided the written protocol is strictly adhered to.
- Patient positioning is probably the most variable condition in the clinical setting.

- Patient mevement should be checked for by careful inspection of the scan produced, before the patient leaves the scan table.
- Using large ROI's such as Gruen zones yields significantly better precision than smaller ROI's.
- Patients with intense ectopic ossification are not suitable candidates for longitudinal study.

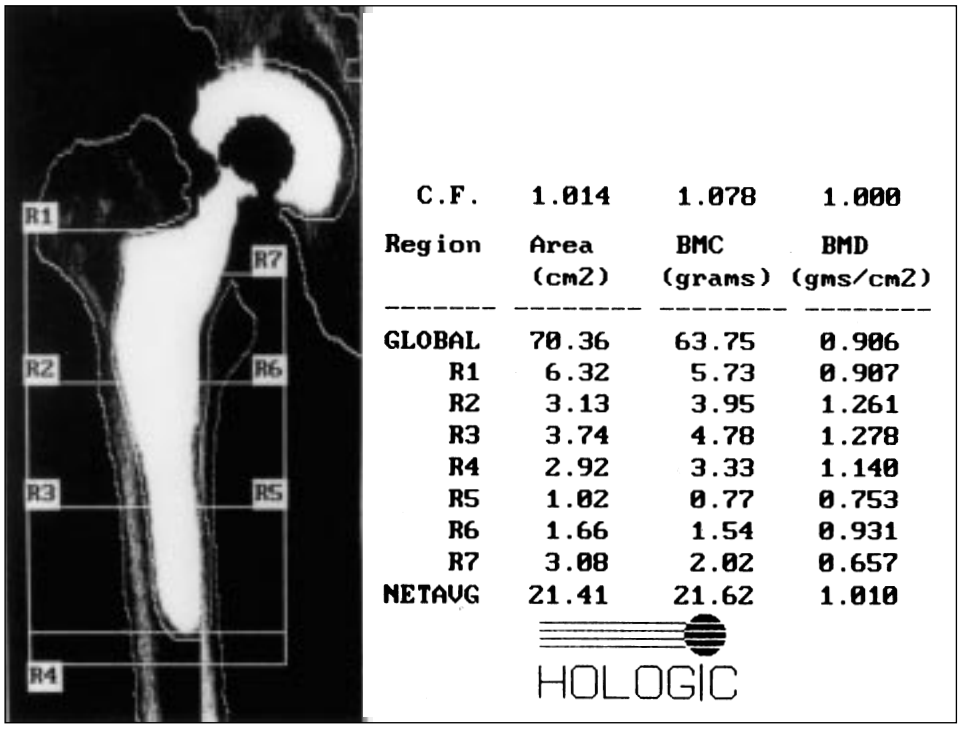

Fig. 3 A - *DEXA scan image when patient moved during the scanning, causing severe image distortion easily noted in the neck of the prosthesis. The BMD values produced in zones 5 and 6 are severely reduced below the true values.*

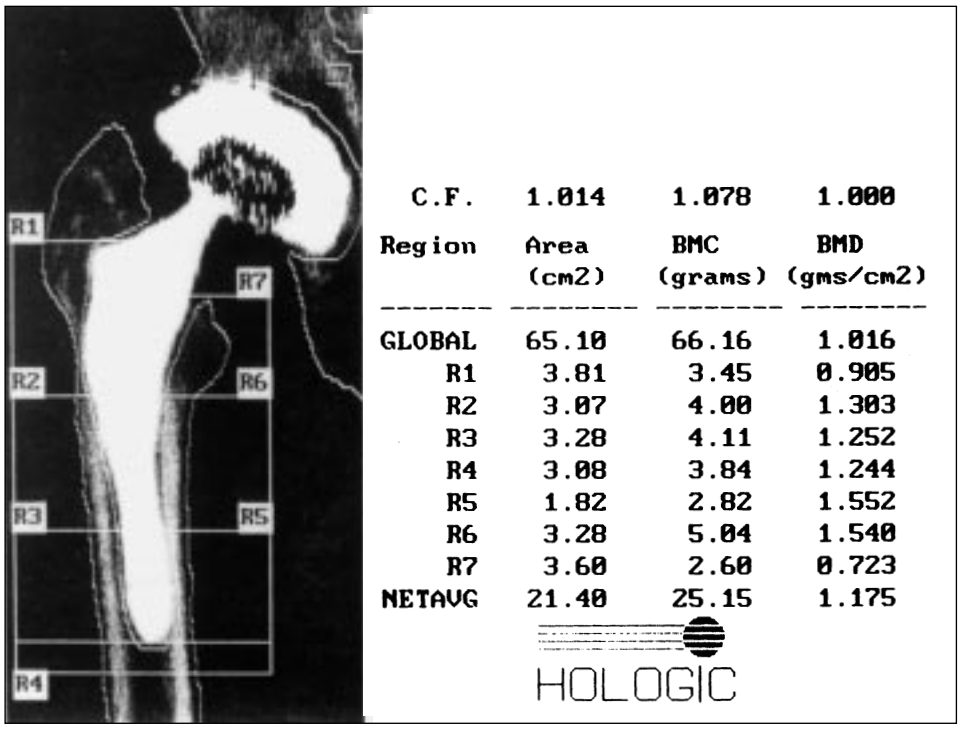

Fig. 3 B - *Repeated corrected DEXA scan image of the same patient without movement, showing true values in zones 5 and 6.*

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