Osteoporos Int (2000) 11:68–75

Osteoporosis International

Original Article

Long-Term Precision of DXA Scanning Assessed over Seven Years in Forty Postmenopausal Women

R. Patel[1], G. M. Blake[1], J. Rymer[2] and I. Fogelman[1]

[1]Department of Nuclear Medicine, and [2]HRT Research Unit, Guy's Hospital, London, UK

Abstract. The reproducibility of dual-energy X-ray absorptiometry (DXA) measurements of bone mineral density (BMD) is an important factor for longitudinal studies. We assessed the long-term precision of postero-anterior lumbar spine, femoral neck and total hip BMD in 40 postmenopausal women who formed the control arm of a clinical trial of tibolone. BMD was measured at 0, 6 and 12 months and thereafter every 12 months up to 7 years. For each subject the trend of BMD with time was analyzed using linear regression. Each residual was expressed as the percentage difference from predicted BMD and the validity of assuming linear change with time was checked using the mean residuals for each visit number. For spine BMD a chi-squared test showed that the mean residuals were not statistically significantly different from zero. Although statistically significant deviations from linearity were found for the femoral neck and total hip sites the weighted root mean square residuals were small compared with the precision errors. When residuals were binned into histograms a statistical test for skewness was not significant for all three sites. However, a test for kurtosis yielded a statistically significant result for each histogram due to outlying residuals. To determine the standard deviation (SD) of the core gaussian distribution, outliers were trimmed using the method of Melton et al. For lumbar spine BMD outliers with residuals exceeding $\pm$ 3 SD arose mainly from subjects with a body mass index (BMI) >28 kg/m^2 or from subjects who had undergone a large change in BMI during the study. For femoral neck BMD and total hip BMD the outliers were frequently due to inconsistent rotation of the hip. Results for long-term precision calculated from the standard deviation of residuals using the trimmed (untrimmed) data were: lumbar spine BMD, 1.12% (1.65%); femoral neck BMD, 2.21% (2.48%); and total hip BMD, 1.32% (1.57%). These errors were only slightly worse than short-term errors despite changes of DXA scanner during the course of the study. However, obesity may have an adverse effect on precision errors in individual patients and particular care is necessary to ensure reproducible patient positioning for femur scans.

Keywords: Bone mineral density; Dual-energy X-ray absorptiometry; Long-term precision

Correspondence and offprint requests to: R. Patel, Department of Nuclear Medicine, Guy's Hospital, St Thomas Street, London SE1 9RT, UK. Tel: +44 (0) 171 955 4855. Fax: +44 (0) 171 955 4657. e-mail: r.patel@umds.ac.uk

Introduction

Dual-energy X-ray absorptiometry (DXA) provides a sensitive, safe and precise method of measuring changes in bone mineral density (BMD) at selected sites in the skeleton [1,2]. Because of its high precision, long-term stability of calibration and low radiation dose [3–6] DXA scanning is widely used for prospective clinical trials of new therapies to prevent bone loss in postmenopausal women [7–10]. DXA is also used for identifying postmenopausal women with low bone density who can then be advised to take hormone replacement therapy or other preventive treatment [11,12]. Such patients often receive follow-up scans after 1 or 2 years to assess their response to therapy [13].

High precision is an important issue for longitudinal studies because it determines the smallest change in bone density that can be detected [13,14] and can therefore influence the number of subjects required in a clinical trial [4] or the length of time before a follow-up scan is likely to show evidence of significant change

[15]. To decide whether a follow-up measurement provides evidence of a significant and clinically relevant change in BMD a knowledge of the precision errors of the technique is required. It is widely accepted that for a single baseline measurement and a single follow-up measurement the smallest change that can be regarded as statistically significant at the 95% confidence level is approximately 3 times the precision error [13,14].

Most studies of new instrumentation or new applications include a measurement of precision. This entails performing a sufficient number of repeated measurements on a representative set of individuals to quantify the reproducibility of the technique accurately [16]. For reasons of speed and convenience it is general practice to evaluate only the short-term precision errors from repeated measurements performed either on the same day or extending over a period of time of no more than a few weeks. Over such short time periods no true change in BMD is expected and the precision error is usually expressed by the coefficient of variation (CV) of repeated measurements [16].

Generally it is more difficult to determine long-term precision errors because they are measured over time periods of months or years in which true changes in BMD may occur. Although short-term precision studies are relatively easy to perform, it is often more relevant to the interpretation of clinical data to know the long-term precision error. Generally, long-term precision errors are likely to be larger than short-term errors because of additional random variations likely to arise from the equipment used (e.g., small drifts in instrumental calibration), changes in soft tissue composition or variations in operator technique or patient positioning.

For the present study we evaluated the long-term precision of spine and hip DXA in 40 postmenopausal women who formed the control arm of an open clinical trial of tibolone and who were followed over 7 years [17].

Subjects and Methods

Definition of Long-Term Precision

It is usual to express the short-term precision error as the coefficient of variation by writing the standard deviation (SD) as a percentage of the mean [16]:

$$\text{CV short-term} = \frac{\text{SD}}{\text{Mean}} \times 100\% \qquad (1)$$

Because of the likely true changes in BMD during the measurement period the calculation of long-term precision errors requires a different mathematical approach from that for short-term precision. If it is assumed that the changes subjects undergo approximate to a linear change in bone density with time then any variation which occurs due to reasons other than the expected linear change can be quantified using regression analysis [16]. When the bone density results of repeat measurements performed on the same subject are plotted against time then the variability about the regression line is quantified by the standard error of the estimate (SEE). The estimate of the long-term precision error for the individual subject is then given by the SEE and can be expressed as the coefficient of variation by writing the SEE as a percentage of the mean:

$$\text{CV long-term} = \frac{\text{SEE}}{\text{Mean}} \times 100\% \qquad (2)$$

It is important to be aware that this definition of long-term precision based on the SEE may still include variability because of nonlinear changes in bone density. It may therefore lead to the true precison errors being overestimated in patients who have recently commenced or discontinued treatment for osteoporosis, or women in the first few years after the menopause [16].

Subjects

The present study was based on a group of 40 postmenopausal women who formed the control arm of a nonrandomized prospective clinical trial carried out to assess the effectiveness of tibolone [17], which is a synthetic compound with weak hormonal properties that does not stimulate the endometrium. At enrolement in the study 50 women received treatment and 50 women took placebo. Five of the women in the control group withdrew at an early stage of the study. The 40 women included in our analysis were those continuing to participate in the study after 2 years. The mean age of subjects on placebo at the start of the study was 52.5 years and all the women were between 6 and 36 months since the menopause (as documented by time since last menstrual period and raised gonadatropin levels). Spine and hip DXA was performed at baseline, 6 months and then every year up to 7 years. All baseline scans were acquired between December 1988 and October 1990. Twenty-nine of the 50 women in the control group were continuing to take part in the study after 7 years. For each subject the trend of BMD with time was analyzed using linear regression. The BMD measurement sites for which the long-term precision was evaluated were posteroanterior (PA) spine (L1–4), femoral neck and total hip. The total hip site was included because it is known to be a region of interest which can be measured with high precision due to its relatively large projected area. Also, the International Committee for Standards in Bone Measurement (ICSBM) has recently advocated the use of the total hip region of interest for the standardization of hip BMD measurements [18].

Changes in DXA Scanner

During the course of the study the following models of Hologic DXA scanners were used (Hologic, Bedford MA):

Table 1. Mean BMD value and precision (CV%) of the Hologic spine phantom shown for each machine used during the course of the study. Also shown are the correction factors arising from in vivo cross-calibration

Hologic scanner	Dates	Mean phantom BMD (g/cm^2)	CV%	In-vivo cross-calibration factors	
				Spine BMD	Femoral neck BMD
QDR-1000	1988–1991	1.028	0.38	1.000	1.000
QDR-2000	1992–1994	1.029	0.46	0.993	0.990
QDR-2000*plus*	1994–1995	1.031	0.47	1.004	0.989
QDR-4500	1995–1997	1.023	0.46	1.014	1.007

Table 2. Short-term precision errors for posteroanterior lumbar spine and femoral neck BMD for different generation Hologic scanners. The number of degrees of freedom (d.f.) indicating the statistical weight of each study is also shown

Precision study	Scanner	Reference	Spine CV	Femoral neck CV	d.f.
Slosman et al. (1990)	QDR-1000	[22]	1.0%	1.6%	60
Orwoll et al. (1991)	QDR-1000	[3]	1.1%	1.2%	20
Blake et al. (1992)	QDR-1000	[23]	0.9%	1.3%	32
Devogelear et al. (1993)	QDR-1000	[24]	1.1%	–	15
Steiger et al. (1991)	QDR-2000	[25]	0.72%	–	24
Slosman et al. (1992)	QDR-2000	[26]	0.60%	–	51
Devogelear et al. (1993)	QDR-2000	[27]	0.82%	0.79%	13
Blake et al. (1994)	QDR-2000	[28]	0.8%	–	48
Fuerst et al. (1995)	QDR-4500	[29]	0.70%	2.00%	33
Baran et al. (1995)	QDR-4500	[30]	0.76%	1.41%	48
Prince et al. (1995)	QDR-4500	[31]	1.34%	1.38%	7

1988–1991: QDR-1000 (pencil beam mode)
1992–1994: QDR-2000 (pencil beam mode)
1994–1995: QDR-2000*plus* (pencil beam mode)
1995–1997: QDR-4500 (array mode)

Daily quality control was performed throughout this period using the same Hologic spine phantom provided by the manufacturer for the QDR-1000 system. Each new bone densitometer installed during the course of the study was cross-calibrated in vitro with the previous DXA scanner using the same spine phantom used for daily quality control. In each instance the results of the in vitro cross-calibration were checked with an in vivo cross-calibration study [19–21]. The relevant correction factors were used to modify the BMD data used in the present evaluation (Table 1). The precision errors were assumed to be the same for all the above instruments. This assumption was made following the examination of published data for the short-term precision figures (Table 2), which were approximately the same for each generation of machine [22–31].

Statistical Methods

Before pooling the precision errors measured in individual subjects to derive the final estimate of overall precision, it was necessary to determine whether the precision errors should be combined by expressing them in absolute units or on a percentage basis [32]. Pairs of scatter plots for each measurement site were drawn comparing the trend for the SEE values and long-term CV values measured in individual subjects with mean BMD. The results of this analysis showed that while the SEE plots showed a statistically significant correlation with BMD the equivalent plots for CV were not statistically significant. This suggests that the long-term precision data were best expressed by combining data from individual subjects expressed as coefficients of variation.

For this reason each residual was expressed as the percentage difference from the predicted BMD value calculated from the regression line. The mean value of residuals for each annual visit was plotted to check the validity of the assumption that subjects underwent a linear change in BMD with time. All the residuals were then binned to form histograms for PA spine BMD, femoral neck BMD and total hip BMD, and the number of residuals in each histogram and the root mean square standard deviation (SD) were used to determine the best-fitting normal distribution. A statistical test for skewness was also performed and the wings of each distribution were examined by performing a test for kurtosis. The kurtosis test yielded a statistically significant result for each histogram. It was apparent that this was due to the extreme values of residuals at either end of each

distribution. The iterative algorithm of Melton et al. [33] was therefore used to trim the outlying residuals and determine the SD of the core gaussian distribution. In this method the 25th percentile (Q1) and the 75th percentile (Q3) were calculated and the interquartile range (IQR) determined. Residuals more than 1.5 times IQR below Q1 or above Q3 were then removed and Q1, Q3 and IQR recalculated for the remaining residuals. The analysis was repeated until no more residuals were excluded. The best-fitting normal distribution function was then established for the remaining residuals (which were all approximately between the $\pm$ 3 SD limits). Results for the long-term precision were calculated from the standard deviation of residuals using both the trimmed and untrimmed data.

The reasons for the extreme residuals were investigated by plotting the CV value for individual subjects against body mass index (BMI = weight (kg)/height^2 (m^2)) and change in BMI during the study.

Results

Figure 1A–C show examples of subjects who demonstrated (i) a steep linear fall in BMD and (ii) a less rapid but still linear fall in BMD, for the PA spine, femoral neck and total hip sites respectively.

Following initial data analysis using linear regression, values of SEE and long-term CV for each subject were plotted against BMD to determine the optimum way of combining data from the individual subjects. When the correlation coefficients for each of the six scatter plots were calculated the results and their statistical significance were as follows: PA spine SEE, r = 0.384 (p = 0.007); PA spine CV, r = 0.105 (not significant); femoral neck SEE, r = 0.299 (p = 0.03); femoral neck CV, r = 0.037 (not significant); total hip SEE, r = 0.121 (not significant); total hip CV, r = 0.125 (not significant). For PA spine and femoral neck BMD the SEE plot showed a statistically significant positive correlation with BMD, while the equivalent CV plot was not statistically significant. For the total hip site there was no difference between the two approaches. It followed that the long-term precision data were best expressed as coefficients of variation, i.e., as fixed percentages of BMD.

The validity of assuming that subjects undergo linear change with age was checked by plotting the mean value of the residuals for each annual visit. Results of a goodness-of-fit analysis using the chi-squared test showed that for the spine these were not statistically significantly different from zero (Fig. 2A). For femoral neck and total body the residuals were statistically significant but the weighted root mean square residuals were small compared with the short-term precision errors in Table 1 (Fig. 2B,C).

Each residual was then expressed as the percentage difference from the BMD value predicted from linear regression analysis and plotted in a histogram (Fig. 3A–C). Results from a statistical test for skewness were not significant for all three sits. A test for kurtosis produced statistically significant results for each histogram due to extreme values of residuals at either end of each distribution. Outliers exceeding $\pm$ 3 SD were trimmed using the method of Melton et al. [33]. Results for the long-term precision calculated using the trimmed (untrimmed) data were 1.12% (1.65%) for lumbar spine BMD, 2.21% (2.48%) for femoral neck BMD and 1.32% (1.57%) for total hip BMD.

When the extreme residuals were investigated by

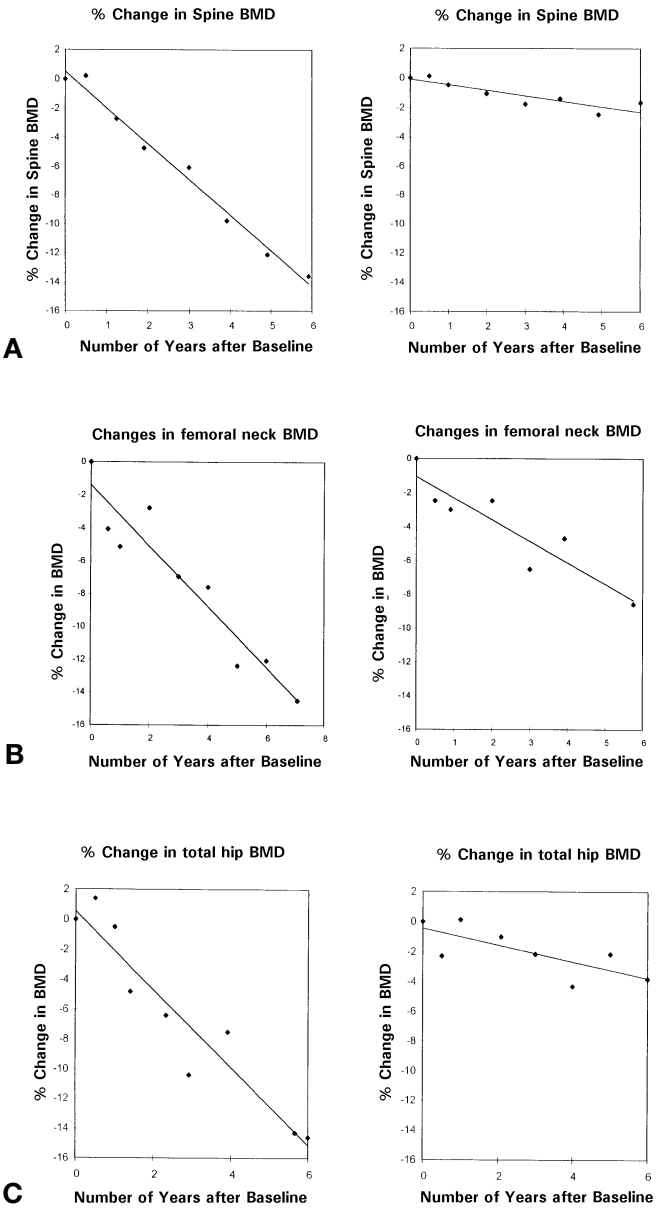

Fig. 1. A Examples of subjects who demonstrated (i) a steep linear fall in BMD and (ii) a less rapid but still linear fall in BMD for the posteroanterior (PA) spine site. **B** Similar plot to **A** but for the femoral neck site. **C** Similar plot to **A** but for the total hip site.

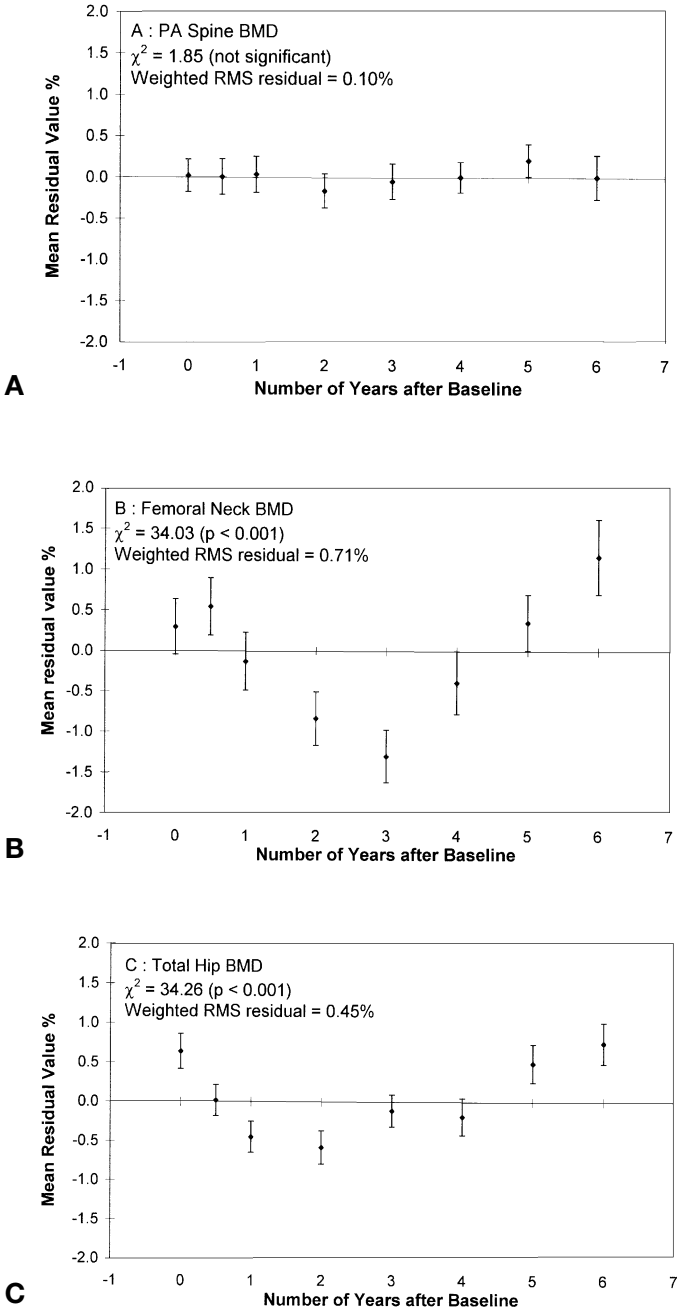

Fig. 2. A Mean value of residuals for each annual visit for PA spine BMD. Error bars show $\pm$ 1 SEM. The root mean square (RMS) residuals were weighted for the number of residuals at each visit. Similar plot to **A** but for femoral neck BMD. **C** Similar plot to **A** but for total hip BMD.

plotting the CV value for individual subjects for PA spine BMD against BMI and change in BMI during the course of the study, both results were found to be statistically significant (r = 0.377, p = 0.015 and r = 0.448, p = 0.003 respectively) (Fig. 4A, B). Hip BMD outliers appeared to be unaffected by BMI but frequently arose due to inconsistent positioning of the hip.

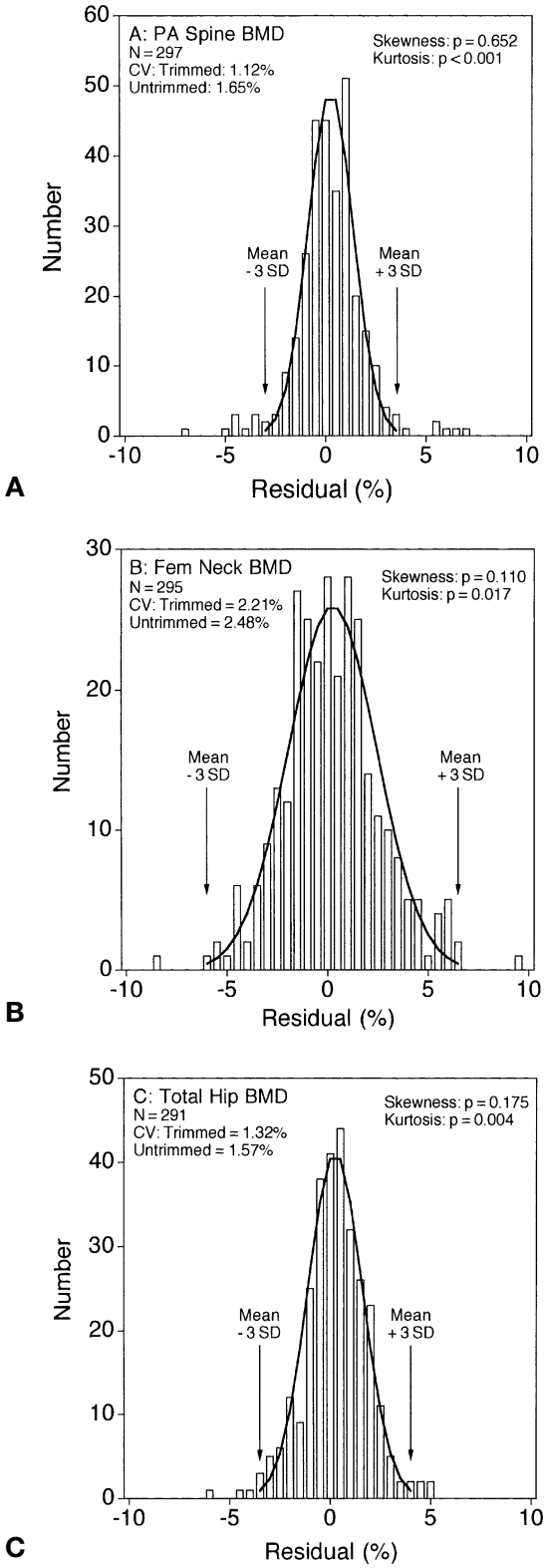

Fig. 3. A Histogram of residuals for PA spine BMD. Each residual is expressed as the percentage difference from the BMD value predicted from linear regression analysis. *N* is the total number of residuals in plot. CV values are shown with and without trimming for outliers. *Continuous curve* shows gaussian fit to trimmed data. **B** Similar histogram to **A** but for femoral neck BMD. **C** Similar histogram to **A** but for total hip BMD.

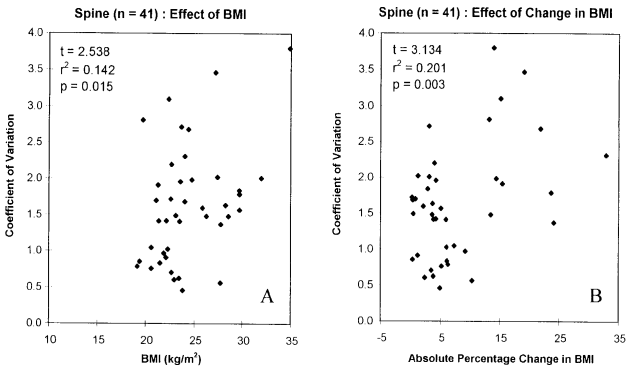

Fig. 4. Scatter plots for CVs of individual subjects plotted against **A** body mass index (BMI) at baseline and **B** change in BMI between baseline and final BMD measurement.

Discussion

In many osteoporosis centers, patients attending outpatient clinics or recommended to take preventive treatment may have one or more follow-up scans. Verifying response to medication is widely believed to have a beneficial function in encouraging compliance with treatment. However, realistic figures for the long-term precision error are essential for the proper evaluation of follow-up scans since they enable a set of clear rules to be drawn up for determining whether the measured changes in BMD indicate a statistically significant response to treatment, or whether BMD is unchanged, or perhaps continuing to fall significantly. In calculating the smallest detectable change in BMD it is necessary to allow not just for the precision error but also for the statistical significance and power required, since these must be chosen to reflect the importance attached to avoiding a false negative (a type II error) as well as a false positive finding (a type I error). If CV is the coefficient of variation of the long-term precision error then, because both measurements are affected by precision errors, a 1 SD difference between the initial baseline and a follow-up investigation will be $\sqrt{2}$CV%. The statistical significance of a measured percentage change in BMD of ΔBMD% is therefore:

$$Z_\alpha + Z_\beta = \Delta\text{BMD}\%/\sqrt{2}\text{CV} \qquad (3)$$

where α is the significance level for a type I error and β is the power for a type II error. If a 10% significance level is chosen (Z_α = 1.28) and 80% power (Z_β = 0.84) then Eq. (3) becomes:

$$\Delta\text{BMD}\% = 3\text{CV} \qquad (4)$$

Eq. (4) defines a figure for the smallest change in BMD that must occur before the clinician can determine with 10% significance and 80% power that a patient's BMD result has shown a statistically significant response to treatment. This equation is only valid for a pair of measurements and can be improved upon when multiple measurements are performed [34].

Previous studies have reported figures for the short-term precision for different generation Hologic scanners which vary from 0.7% t 1.34% for the lumbar spine and 0.79% to 2.00% for the femoral neck (Table 2). Results for long-term precision from the present study of 1.65% for the lumbar spine and 2.48% for the femoral neck (using the untrimmed data) appear to be slightly worse than the published results for short-term precision. However, short-term precision studies are likely to be performed under optimal conditions, often on young normal subjects. Results for CV will depend on the group of patients chosen for the study, i.e. young normal subjects, healthy postmenopausal women or osteoporotic subjects. In general with DXA the CV is expected to differ between these groups. It is difficult to establish how significantly such factors will contribute to the differences between the long-term precision errors found in the present study and the short-term errors listed in Table 2.

Precision studies should include a sufficiently large number of repeated measurements to avoid large random statistical errors. If m repeated measurements are made on each of n subjects, there will be a total of $n \times m$ measurements. For studies of short-term precision it is necessary to calculate the mean BMD of each subject and there are only $n \times (m-1)$ independent measurements from which to evaluate precision. In the present study the change in BMD with time was analyzed using linear regression. Since this involves fitting both the slope and the intercept there are only $n \times (m-2)$ independent measurements from which to evaluate precision. This number is the degrees of freedom and is an essential item of information for evaluating the statistical weight of a study. The number of degrees of freedom are shown in Table 2 for the short-term precision studies listed. Gluer et al. [16] recommend at least 27 degrees of freedom as necessary for a satisfactory precision study. In the present study up to 8 BMD meaurements were performed on each of 40 subjects. The number of degrees of freedom is therefore given by the total number of measurements (N in Fig. 3) minus 80 and was 217 for the PA spine data. The number of measurements is not the same for all three sites because a small number of measurements were discarded due to movement or metal artifacts. For the total hip site there are fewer measurements than for the femoral neck site as some scans were acquired without the minimum required length along the shaft of the femur to properly position the total hip region of interest.

An important limitation of the present study was the assumption that subjects were undergoing a linear decrease in BMD with time. To examine this issue the data were analysed for systematic deviations from linearity by expressing each measurement in each patient as the residual from the regression line and plotting the trend of the mean of the residuals for each visit (Fig. 2). No significant deviation from linearity was observed for the lumbar spine and, although the residuals were significant for both the hip sites, the root mean square residuals of both femoral neck and total hip BMD were

small compared with the precision errors. Subjects were on average 21 months since their last menstrual period and therefore were expected to show the effect of the rapid decrease in BMD normally observed in the first few years after the menopause. The expected effect was seen in the hip residual data (Fig. 2B, C) but not the spine (Fig. 2A). The effect of the root mean square residuals in Fig. 2 on the magnitude of the long-term precision errors is to generate the apparent precision error in Fig. 3 by adding in quadrature to the true errors. On this basis the apparent long-term precision errors of 1.12%, 2.21% and 1.32% for PA spine, femoral neck and total hip sites reduce to 1.12%, 2.08% and 1.24%, respectively. However, these corrected figures still entail an assumption that all subjects follow the trends shown in Fig. 2 and hence may still overestimate the true long-term precision errors.

Another limitation of the study was the assumption that the residuals were normally distributed. Whereas none of the distributions showed evidence of skewness, the outlying residuals for all three sites gave rise to statistically significant results for kurtosis. The method for trimming outliers was adopted to fit the core of the gaussian function. Patients' weight or BMI is expected to affect precision because of the increased attenuation and variation in soft tissue composition. Examination of the extreme residuals present in the spine histogram data (Fig. 3A) confirmed that they tended to arise in subjects with a large BMI. Scatter plots for CVs of individual subjects showed statistically significant correlations when plotted against BMI ($p = 0.015$) and change in BMI ($p = 0.003$) (Fig. 4). In a previous study investigating the effect of weight change on DXA scans in a 2 year trial of etidronate therapy [35], the authors found that weight change in a longitudinal study of postmenopausal women did not cause systematic errors in the results of DXA studies of spine and femoral neck BMD but could adversely affect precision. These conclusions are supported by the findings of the present study, which also identified change in BMI as a factor which influences long-term precision. This is likely to be due to the change in soft tissue composition. Examination of the DXA scan images for the femoral neck and total hip indicated that the outliers for these sites arose due to subjects for which the positioning of the hip had been inconsistent – a factor previously shown to cause poor precision in femur BMD measurements [36]. This study confirmed that total hip BMD measurements have better precision than femoral neck BMD measurements – a finding that is likely to relate to the larger projected area of the total hip region of interest.

In conclusion, long-term precision errors were found to be only slightly worse than short-term errors despite the long time period of the study and frequent changes of DXA scanner during the course of the study. However, obesity and change in weight may have an adverse effect on precision errors in individual patients and should be borne in mind when interpreting the results of follow-up scans. Particular care is necessary to ensure reproducible patient positioning for femur scans.

References

1. Cullum ID, Ell PJ, Ryder JP. X-ray dual photon absorptiometry: a new method for the measurement of bone density. Br J Radiol 1989;62:587–92.
2. Genant HK, Engelke K, Fuerst T, et al. Non-invasive assessment of bone mineral and structure: state of the art. J Bone Miner Res 1996;11:707–30.
3. Orwoll ES, Oviatt SK. Longitudinal precision of dual-energy X-ray absorptiometry in a multicenter study. J Bone Miner Res 1991;6:191–7.
4. Gluer C-C, Faulkner KG, Estilo MJ, et al. Quality assurance for bone densitometry research studies: concept and impact. Osteoporos Int 1993;3:227–35.
5. Faulkner KG, McClung MR. Quality control of DXA instruments in multicenter trials. Osteoporos Int 1995;5:218-27.
6. Njeh CF, Fuerst T, Hans D, et al. Radiation exposure in bone mineral density assessment. Appl Radiat Isotopes 1999;50:215–36.
7. Storm T, Thamsborg G, Steiniche T, et al. Effect of intermittent cyclical etidronate therapy on bone mass and fracture rate in women with post-menopausal osteoporosis. N Engl J Med 1990;322:1265–71.
8. Liberman UA, Weiss SR, Broll J, et al. Effect of oral alendronate on bone mineral density and the incidence of fractures in postmenopausal osteoporosis. N Engl J Med 1995;333:1437–43.
9. Herd RJM, Balena R, Blake GM, et al. The prevention of early postmenopausal bone loss by cyclical etidronate therapy: a 2-year double-blind placebo-controlled study. Am J Med 1997;103:92–9.
10. Delmas PD, Bjarnason NH, Mitlak BH, et al. Effects of raloxifene on bone mineral density, serum cholesterol concentrations, and uterine endometrium in postmenopausal women. N Engl J Med 1997;337:1641–7.
11. Kanis JA, Delmas P, Burckhardt P, et al. Guidelines for the diagnosis and management of osteoporosis. Osteoporos Int 1997;7:390–406.
12. Eddy DM, Johnston CC, Cummings SR, et al. Osteoporosis: cost effectiveness analysis and review of the evidence for prevention, diagnosis and treatment: the basis for a guideline for the medical management of osteoporosis. Osteoporos Int 1998; 8 (Suppl 4):S7–S80.
13. Eastell R. Assessment of bone density and bone loss. Osteoporos Int 1996;6(Suppl 2):S3–5.
14. Blake GM, Wahner HW, Fogelman I. The evaluation of osteoporosis: dual-energy X-ray absorptiometry and ultrasound in clinical practice. London: Martin Dunitz, 1999:152–4.
15. Gluer C-C. How to characterise the ability of a diagnostic technique to monitor skeletal changes. J Bone Miner Res 1997;12(Suppl 1):S378.
16. Gluer C-C, Blake GM, Lu Y, et al. Accurate assessment of precision errors: how to measure the reproducibility of bone denisitometry techniques. Osteoporos Int 1995;5:262–70.
17. Rymer J, Chapman MG, Fogelman I. Effect of tibolone on postmenopausal bone loss. Osteoporos Int 1994;4:314–9.
18. Hanson J. Standardization of femur BMD [letter]. J Bone Miner Res 1997;12:1316–7.
19. Blake GM, Parker JC, Buxton FMA, et al. Dual x-ray absorptiometry: a comparison between fan beam and pencil beam scans. Br J Radiol 1993;66:902–6.
20. Blake GM, Fogelman I. Replacing dual x-ray absorptiometry scanners: cross-calibration of a new multidetector array system. J Bone Miner Res 1995;10(Suppl 1):S267.
21. Blake GM. Replacing DXA scanners: cross-calibration with phantoms may be misleading. Calcif Tissue Int 1996;59:1–5.
22. Slosman DO, Rizzoli R, Buchs B, et al. Comparative study of the performances of X-ray and gadolinium-153 bone densitometers at the level of the spine, femoral neck and femoral shaft. Eur J Nucl Med 1990;17:3–9.
23. Blake GM, Fogelman I. New developments in bone density measurements by dual X-ray absorptiometry. Adv Hosp Technol 1992;3:5–16.

24. Devogelear JP, Baudoux C, de Deuxchaisnes C. Lack of precision of the lumbar BMD measurements with the QDR-1000/W when patients are lying in a lateral position. Calcif Tissue Int 1993;52:163.
25. Steiger P, Von Stetton E, Weiss H, et al. Paired AP and lateral supine dual X-ray absorptiometry of the spine: initial results with a 32 detector system. Osteoporos Int 1991;1:190.
26. Slosman DO, Rizzoli R, Donath A, et al. Bone mineral density of lumbar vertebral body determined in supine and lateral decubitus: study of precision and sensitivity. J Bone Miner Res 1992;7:S192.
27. Devogelear JP, Baudoux C, de Deuxchaisnes C. Reproducibility of BMD measurements on the QDR-2000 Hologic Inc. Calcif Tissue Int 1993;52:164.
28. Blake GM, Jagethesan T, Herd RJM, et al. Dual X-ray absorptiometry of the lumbar spine: the precision of paired anteroposterior/lateral studies. Br J Radiol 1994;67:624–30.
29. Fuerst T, Gluer C-C, Genant HK. Performance evaluation of a new bone densitometer: Hologic QDR-4500. J Bone Miner Res 1995;10(Suppl 1):S370.
30. Baran D, Leahey D, Von Stetton E. Clinical evaluation of a fourth generation fan-beam DXA system. J Bone Miner Res 1995;10(Suppl 1):S374.
31. Prince R, Price R, Gutteridge D, et al. Comparison of bone mineral density measurement between the Hologic QDR2000 and the QDR4500A. J Bone Mineral Res 1995;10(Suppl 1):S272.
32. Blake GM, Roe D, Lazarus CR. Long-term precision of glomerular filtration rate measurements using ^{51}Cr-EDTA plasma clearance. Nucl Med Commun 1997;8:776–84.
33. Melton LJ, Lane AW, Cooper C, et al. Prevalence and incidence of vertebral deformities. Osteoporos Int 1993;3:113–9.
34. Schlessman JJ. Planning a longitudinal study. II. Frequency of measurement and study duration. J Chron Dis 1973;26:561–70.
35. Patel R, Blake GM, Herd RJM, et al. The effect of weight change on DXA scans in a 2-year trial of etidronate therapy. Calcif Tissue Int 1997;61:393–9.
36. Wilson CR, Fogelman I, Blake G, et al. The effect of positioning on dual energy x-ray bone densitometry of the proximal femur. Bone Miner 1991;13:69–76.

Received for publication 30 March 1999
Accepted in revised form 22 June 1999