Accuracy of Lumbar Spine Bone Mineral Content by Dual Photon Absorptiometry

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The accuracy of measurements of the bone mineral content (BMC, g) and bone mineral density (BMD, g/cm^2) of the lumbar spine by dual photon absorptiometry (DPA) was estimated by means of two different spine scanners (a Nuclear Data 2100 and a Lunar Radiation DP3). The lumbar spines of 13 cadavers were used. BMC and BMD were measured in situ and on the excised vertebrae in a solution of water/ethanol; and covered with ox muscle/porcine muscle/lard. The actual mineral weight and areal density were determined after chemical maceration, fat extraction, drying to a constant weight, ashing for 24 hr at 600°C, and correction for the transverse processes. The true area was measured by parallax free X rays and planimetry. All measurements of BMC or BMD were highly interrelated ($r = 0.94–0.99$). The standard error of estimate (s.e.e.) of BMC in situ versus BMC in water/ethanol was 5.2%. The agreement between the BMD values of the two scanners was very good (s.e.e. = 2.9%). BMC in situ predicted the actual vertebral mineral mass with an s.e.e. of 8.1%. BMD in situ and BMD in water/ethanol predicted the actual area density with s.e.e.s of 10.3% and 5.0%, respectively. This study discloses the correlation and accuracy error of spinal DPA measurements in situ in whole cadavers versus the actual BMC and BMD. The error, which is underestimated in in vitro studies, amounts to 10%.

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The magnitude of the accuracy error of lumbar spine scanning for measuring the bone mineral content (BMC) by dual photon absorptiometry (DPA) varies in the literature. This apparent inconsistency is mainly caused by different approaches to the detection of different sources of error (*1–6*). Once the basic problems of linearity, efficiency of edge-detection routines, and varying absorber thickness have been dealt with one major issue remains: the error deriving from varying or inhomogeneous fat content in the internal or external environment of the vertebrae. Wahner et al. (*7*) recently published a study of successive extraction of fat from excised vertebrae. In the same paper they reported the results of measuring lumbar spine BMC in situ in three cadavers, and in the excised vertebrae embedded in water. However, no data are available in the literature on the measuring setup, which is closest to describing the overall in vivo accuracy error, namely a comparison between lumbar spine BMC in whole cadavers and the actual mineral content of the vertebrae in question. The present study on the vertebrae of 13 cadavers was conducted in order to elucidate this relation.

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MATERIALS AND METHODS

BMC of the lumbar spine was measured by DPA using gadolinium-153 sources of 1 Ci. Two different scanners were used: The first was a prototype of the Nuclear Data 2100 spine scanner which was built at Mølsgaard Medical and developed in collaboration with our laboratory. The software used in this study for operating the scanner and calculating the data was written in our laboratory. The second scanner was a Lunar Radiation DP3 spine scanner. The principles of DPA are described in detail elsewhere (*2,5,6,8–10*). The mode of operation of the two scanners is related, as are the computational routines. Both scanners employ the so-called Rst-averaging in soft-tissue points before calculation of the BMC (*10*), and, furthermore, in both scanners the baseline and the edges are found by the computer followed by adjustment by the operator if needed. However, the mechanical parts and specific software writing are particular for each apparatus. A comparison of the technical specifications of the two instruments is given in Table 1. The software used with the Lunar DP3 in this study was the 7E version. In order to compare the results from the

TABLE 1
Technical Specifications of the Two Instruments for Measuring Lumbar Spine Bone Mineral Content by Dual Photon Absorptiometry

	Nuclear data 2100	Lunar DP3
Transverse scan speed (mm/sec)	4.0	2.5
Line spacing (mm)	4.0	4.5
Countrate collection intervals (sec)	0.5	0.5
Source collimation (mm)	3.0	3.2
Detector collimation (mm)	9.0	8.0

two scanners several calibrations were performed on the same set of standards. The selected region of interest on both scanners was the vertebrae L_2–L_4. The lumbar spine bone mineral density (BMD), which is an areal density, was calculated by division by the projected scanned area.

Thirteen cadavers were used in the study. They were obtained from the Department of Pathology at Glostrup Hospital and the Institute of Forensic Medicine, University of Copenhagen. The age, cause of death, and other clinical characteristics are given in Table 2. Necropsies with malignant bone disease or known bone metastases were excluded from the investigation.

BMC of the lumbar spines was measured three times with the Nuclear Data 2100 Spine Scanner—before removal; in vitro embedded in a mixture of water and ethanol (71.4% water w/w, liquid height 16 cm), and with a covering of 2 cm ox muscle, 2 cm porcine muscle, and 5 mm lard. Furthermore, the BMC was measured once with the lumbar spines embedded in the 16 cm water/ethanol solution using the Lunar Radiation DP3 scanner. The 71.4% water/ethanol solution was chosen to simulate human tissue with a lean/fat ratio of 71.4%. The 71.4% is given by the convenience of mixing by volume two-thirds of water and one-third of ethanol. The Rst value (*10*) of that solution is ~1.45 which also approximates the Rst value found in humans with 70%–80% lean tissues. The combination of a piece of lean ox muscle, porcine muscle and lard was used to include the extremes of mammal tissue. The Rst value turned out to be ~1.50, which corresponds to the Rst value in humans with ~95% lean tissues. The total thickness of the tissue layer (4.5 cm) was chosen to simulate a thin person. This relatively thin absorber thickness may cause deadtime correction problems. However, the source used in this study for both instruments had lived for one half-life, and, furthermore the influence of deadtime events is corrected for in the software. As the aim of the study was to investigate the accuracy of DPA, we attempted to minimize the influence of the precision error on the comparison between different measuring situations. Thus, once the BMC of a particular cadaver had been measured in situ, and the region of interest determined, all consecutive in vitro measurements of that particular specimen were related to the initially determined region of interest.

The lumbar spines were removed from the cadavers in one piece and processed as follows: Soft tissue was removed in part with scissors and scalpels and in part with a chemical procedure using three dissolutions: (a) antiformin 5% 18 hr, (b) sodium carbonate 2% 12 hr, and (c) ether/acetone 50%/50% Vol/Vol 24 hr (*11*). The chemically macerated and defatted vertebrae were dried at 60° to a constant weight, and the separate weights of the vertebrae L_2, L_3, and L_4 were recorded. To compensate for the fact that the edge detection routines of the scanners exclude the transverse processes, we determined the fraction of the total weight of each vertebra taken up by its transverse processes. The transverse processes were separated as closely as possible from the vertebral arc, and weighed. The fraction of the total vertebral weight thus determined was 0.2%–4.7% (mean = 2.4%, s.d. = 1.0%). The

TABLE 2
Clinical Data for the Thirteen Cadavers

	Age (years)	Weight (kg)	Height (cm)	Cause of death	Relevant earlier diseases
Premenopausal women					
1	25	58	163	Ethanol poisoning	—
2	35	63	164	AMI	—
Postmenopausal women	67	45	159	Pneumonia	Breast cancer
3					
4	70	45	160	Uraemia	Carcinoma of collum uteri
5	78	48	145	Intracranial lesion	—
6	80	54	157	Pulmonary embolia	—
7	81	45	156	Pneumonia	Malignant melanoma
8	82	56	160	Pulmonary embolia	Carcinoma of sigmoideum
Men	57	63	167	AMI	—
9					
10	60	88	181	AMI	—
11	67	69	169	Pulmonary oedema	—
12	76	89	183	AMI	—
13	90	53	171	Pneumonia	—

true projected area of each vertebral body without transverse processes was measured by parallax free x-rays taken in the anterior-posterior direction. The areas thus obtained were measured by planimetry using a Morphomat 30. The true areal density was calculated as the ash weight minus transverse processes and divided by the projected area. The mineral content of each vertebra was determined as the ash weight after heating at 600°C for 24 hr. The ash content was 54.5%–61.1% (mean = 57.9%, s.d. = 1.4%).

RESULTS

Measurement by the ND 2100 apparatus showed no significant difference between lumbar spine BMC in situ and in 16 cm water/ethanol, and lumbar spine BMC in 16 cm water/ethanol and in a covering of ox muscle, porcine muscle, and lard (Fig. 1). However, there was a significant difference between the BMC in situ and that in the ox muscle/porcine muscle/lard covering ($p < 0.001$, Fig. 1). There was also a significant difference between the BMC in 16 cm water/ethanol measured with the ND 2100 and that measured with the Lunar Radiation DP3 scanner ($p < 0.05$, paired t-test, not shown).

Highly significant correlations were found between the lumbar spine BMC measured in 16 cm water/ethanol, in situ, and the ox/porcine/lard using the ND 2100 apparatus, and in 16 cm water/ethanol using the Lunar Radiation DP3 ($p < 0.001$, $r = 0.95–0.99$, Fig. 2). Furthermore, the slopes were not significantly different from one, and the intercepts not significantly different from zero. The standard error of estimate (s.e.e.) of BMC in situ versus BMC in 16 cm water/ethanol was 5.2%.

With regard to the BMD values the corresponding correlations were all highly significant and in the same order of magnitude ($p < 0.001$, $r = 0.96–0.99$, Fig. 3). None of the regression lines were significantly different from the line of identity excepting the regression between BMD in situ and BMD in water/ethanol, where the slope was significantly different from one. None of the intercepts were significantly different from zero. The agreement between the Lunar and the ND scanners was almost perfect when BMD values were applied (s.e.e. = 2.9%).

Figure 4 gives the correlations between the different lumbar spine BMC measurements and the ash weight of the vertebrae L_2–L_4 corrected for transverse processes. All correlations were highly significant ($p < 0.001$, $r = 0.96–0.98$). Neither of the slopes was significantly different from one, nor were the intercepts significantly different from zero. The standard errors of estimate are given in the figure. With the ND 2100 apparatus the s.e.e.s ranged from 6.1% to 8.1%. BMC measured in situ predicted the actual vertebral mineral mass with an error of 8.1%.

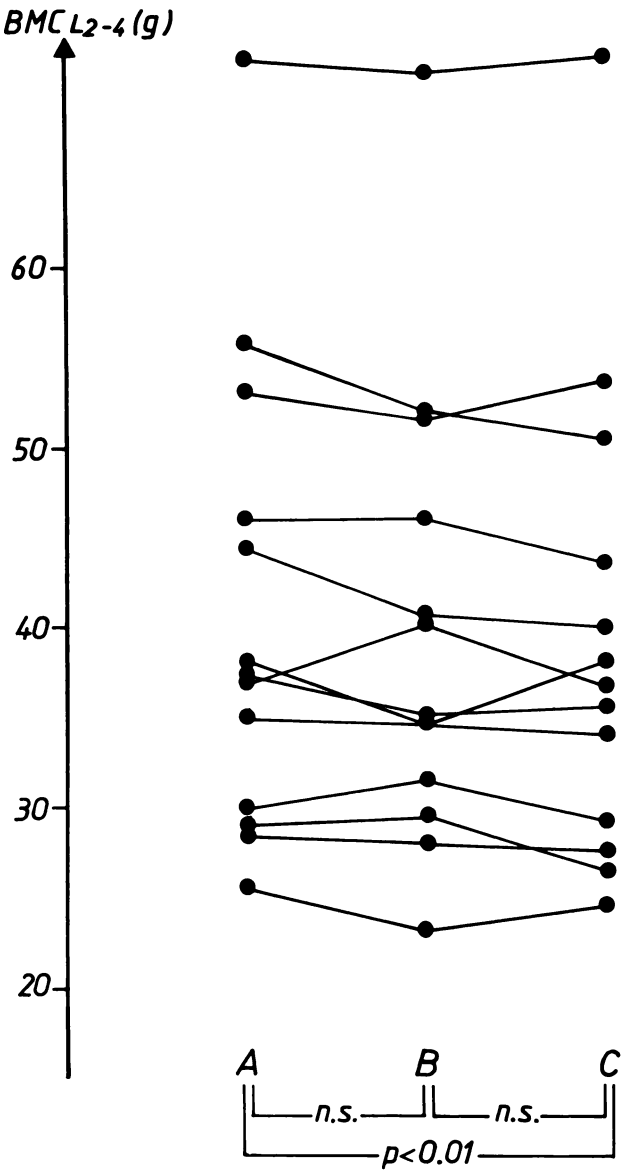

FIGURE 1
Bone mineral content measured on the ND 2100 spine scanner A: In situ; B: in 16 cm water/ethanol (71.4% water w/w); and C: Covered with 2 cm ox muscle, 2 cm porcine muscle, and 5 mm lard. Comparisons by Student's t-test for paired data.

Figure 5 shows the corresponding correlations with regard to the BMD values obtained in the different scanning settings versus the actual areal density (ash weight of the vertebrae L_2–L_4 divided by the projected area of the vertebral bodies). All correlations were highly significant ($p < 0.001$, $r = 0.94–0.99$). None of the intercepts were significantly different from zero, but in all except the comparison between true ashed BMD and BMD in situ by the ND 2100, the slopes were significantly different from, and slightly higher than one ($p < 0.05$). BMD measured in situ with the ND 2100 apparatus predicted the actual areal density with an

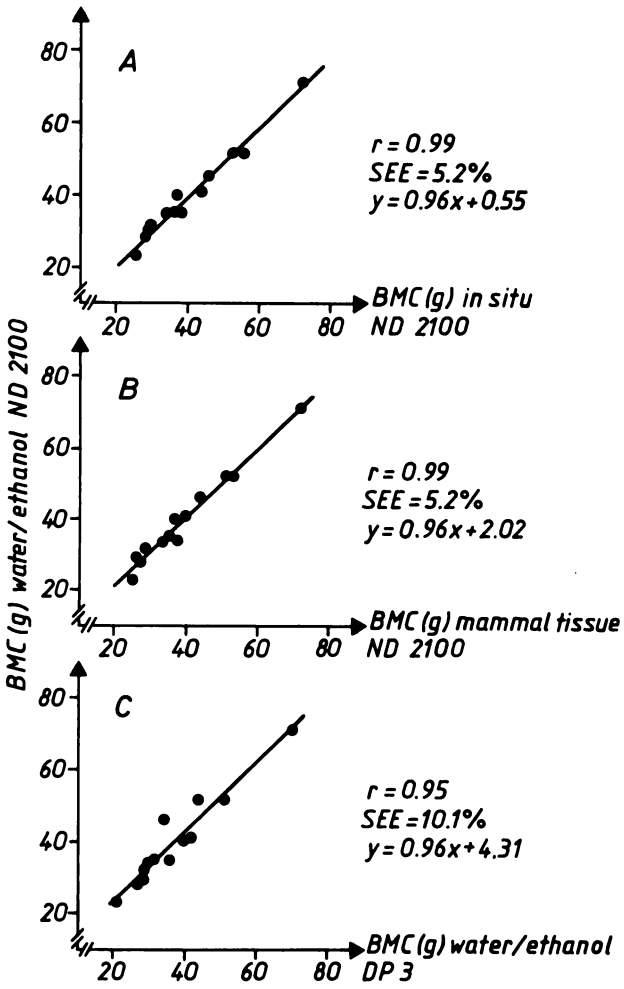

FIGURE 2
Correlations between lumbar spine BMC measured in 16 cm water/ethanol (71.4% water w/w) with the ND 2100 apparatus and A: Lumbar spine BMC measured in situ with the ND 2100; B: Lumbar spine BMC measured in a cover of 2 cm ox muscle, 2 cm porcine muscle, and 5 mm lard with the ND 2100; and C: Lumbar spine BMC measured in 16 cm water/ethanol with the Lunar Radiation DP3 apparatus. Coefficients of correlation, standard errors of estimates (s.e.e.%) and regression equations are given in the figure.

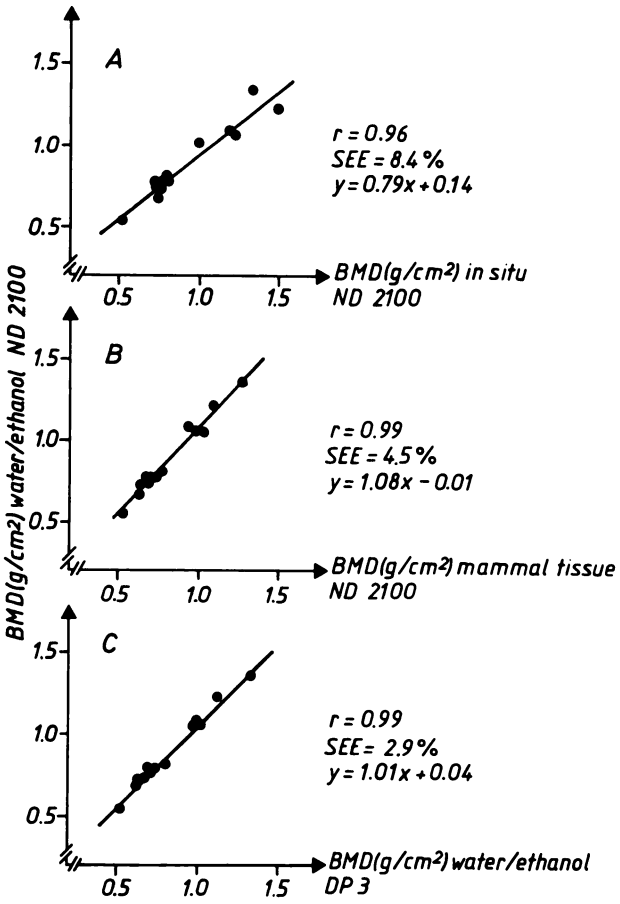

FIGURE 3
Correlations between lumbar spine BMD measured in 16 cm water/ethanol (71.4% water w/w) with the ND 2100 apparatus and A: Lumbar spine BMD measured in situ with the ND 2100; B: Lumbar spine BMD measured in a cover of 2 cm ox muscle, 2 cm porcine muscle, and 5 mm lard with the ND 2100; and C: Lumbar spine BMD measured in 16 cm water/ethanol with the Lunar Radiation DP3 apparatus. Coefficients of correlation, standard errors of estimates (s.e.e.%), and regression equations are given in the figure.

s.e.e. of 10.3%. BMD measured in water/ethanol predicted the actual area density with an s.e.e. of 5–6% using both scanners.

Table 3 shows mean values, as well as parameters of correlations between the true area and the determinations of the projected area by DPA in the four different settings. The true area was ~15% smaller than the projected area determined by DPA.

DISCUSSION

The value for percent mineral in whole dry defatted vertebrae determined by ashing was 57.9% with a range of 54.5–61.1%. This result on these mainly trabecular bone specimens agrees with the results obtained by Burnell et al. (*12*) on another mainly trabecular bone site, namely the iliac crest, investigated by bone biopsy. Burnell et al. (*12*) found the value for percent mineral to be 56 ± 4% in normals, and furthermore reduced to 51 ± 7% in osteoporotic females. Other investigators (*13–16*) including ourselves (*17*) have found higher values for percent mineral of mainly cortical bone specimens: 65–70%.

There was a striking disconcordance between the fraction taken up by the transverse processes found in the present study (2.4%) and that mentioned elsewhere to be chosen because of the edge delineating routine:

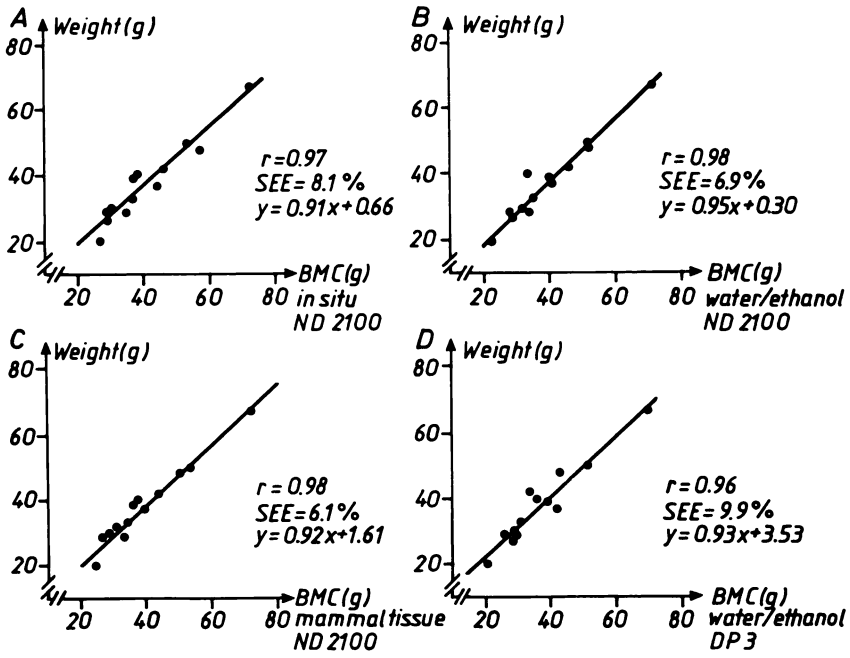

FIGURE 4
Correlations between the actual mineral weight (ash weight) of the vertebrae L_2, L_3, and L_4 and A: Lumbar spine BMC measured in situ with the ND 2100 apparatus; B: Lumbar spine BMC measured in 16 cm water/ethanol (71.4% water w/w) with the ND 2100 apparatus; C: Lumbar spine BMC measured in a cover of 2 cm ox muscle, 2 cm porcine muscle, and 5 mm lard with the ND 2100 apparatus; and D: Lumbar spine BMC measured in 16 cm water/ethanol with the Lunar Radiation DP3 apparatus. Coefficients of correlation, standard errors of estimates (s.e.e.%) and regression equations are given in the figure.

21% (*7*). We cannot account for this difference. The fraction taken up by the transverse processes in the present study was carefully determined by cutting them off as closely as possible from the arc, and thereafter carefully weighing each of them. After removal of the transverse processes there was practically no part of the posterior complex left beyond the most lateral aspects of the vertebral bodies. The rather poor correlations between the true projected area and the scanned projected area determined by DPA (both ND 2100 and DP3, Table 3) clearly indicate that DPA measures something which is not exclusively defined by the projected borders of the vertebral bodies. By comparison of the area determinations in the present study it is seen, that the true projected area is systematically smaller than the area determined by DPA. This renders the true BMD larger than the BMD by DPA (Fig. 5). The uncertainty as to where exactly DPA cuts off the transverse processes by the edge detection routines may reflect problems of selecting the area of interest. Such problems may, in turn, partly be responsible for the large precision error of lumbar BMC and BMD DPA measurements (*18–19*). We have presently shown that the transverse processes make up only 2.4% of total vertebral weight. Furthermore, both we (*20–21*) and others (*22*) have previously demonstrated that it is not

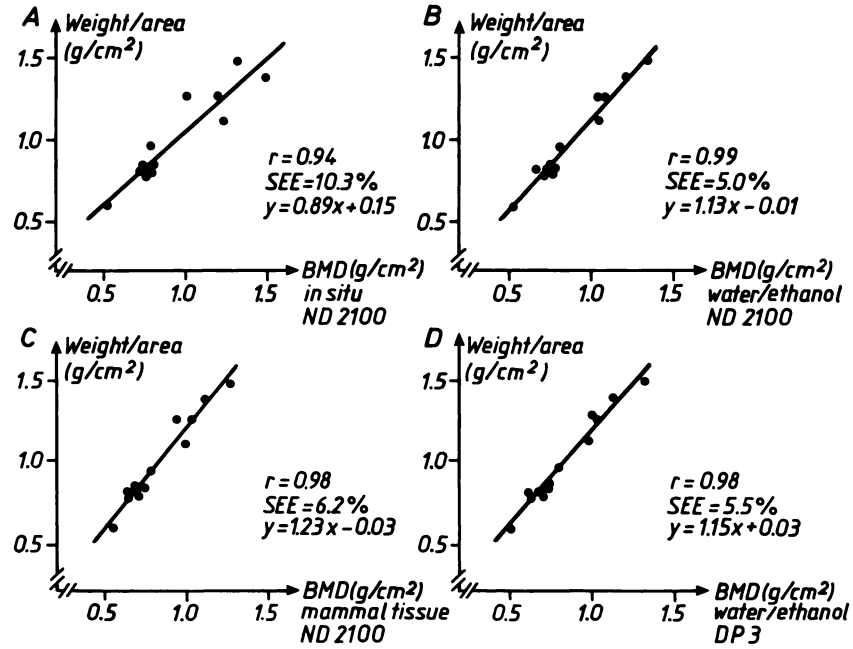

FIGURE 5
Correlations between the actual mineral weight (ash weight) per unit projected area of the vertebrae L_2, L_3, and L_4 and A: Lumbar spine BMD measured in situ with the ND 2100 apparatus; B: Lumbar spine BMD measured in 16 cm water/ethanol (71.4% water w/w) with the ND 2100 apparatus; C: Lumbar spine BMD measured in a cover of 2 cm ox muscle, 2 cm porcine muscle, and 5 mm lard with the ND 2100, and D) lumbar spine BMD measured in 16 cm water/ethanol with the Lunar Radiation DP3 apparatus. Coefficients of correlation, standard errors of estimates (s.e.e.%) and regression equations are given in the figure.

TABLE 3

Correlations Between the True Area of $L_2 + L_3 + L_4$ Determined by Anterior-Posterior Parallax Free X-Rays of the Vertebral Bodies (Dependent Variable), and the Projected Area Determined by DPA in Four Different Settings (Independent Variables)*

	b	y_o (cm^2)	r	s.e.e.%	$\bar{x}$ (cm^2)	s.d. (cm^2)
In situ, ND 2100	0.65	9.66	0.64	11.1	43.82	5.26
Mammal tissue, ND 2100	0.57	11.20	0.83	8.1	47.28	7.75
Water/ethanol, ND 2100	0.62	10.36	0.69	10.5	44.68	5.89
Water/ethanol, DP3	0.54	14.04	0.76	9.5	44.12	7.35
True area	—	—	—	—	38.08	5.29

*The slopes (b), intercepts (y_o), correlation coefficients (r), and standard errors of estimate relative to mean value of the dependent variable (s.e.e.%) are given. The table also shows the mean values ($\bar{x}$) and standard deviations (s.d.) of all five variables (i.e. measurements of area).

very important to distinguish between cortical or trabecular bone changes. We therefore propose that for future use of lumbar DPA measurements the edge detection routines should be simplified so that they do not attempt to exclude the transverse processes. This would improve the precision of lumbar BMC and BMD without deteriorating the accuracy.

Granted our values for actual BMC and BMD are correctly estimated, the finding of high correlation coefficients, slopes which are not different from or close to one and intercepts which are not different from zero combined with rather high s.e.e.s indicate that DPA measurements of the lumbar spine bone mineral have a high local accuracy, although precision errors of the DPA measurement and of the estimation of actual BMC and BMD must play an important role for the magnitude of the estimation error.

It is difficult to compare the accuracy errors reported in the literature, because of differences in the techniques used to measure bone mineral, the type of in vitro setting, the number and part of the vertebrae measured, and finally the part or number of vertebrae that have been defatted, dried and weighed in order to establish the actual mineral weight for comparison with DPA measurements (Table 4) (*2–7*). For instance, in one experiment Wahner et al. (*7*) correlated the BMC of L_2–L_4 to the actual area density of L_3 alone. And in another experiment (*7*) they correlated scan results of single vertebrae from all over the spine to the actual mineral content of the particular vertebrae. On the other hand, the present report correlates scan results of the L_2–L_4 segment to the actual mineral content in this segment.

In correlations of DPA measurements on excised vertebrae in vitro versus the actual BMC or BMD of either the whole scanned part of the spine or a segment of it, the literature shows some agreement with our findings. Only the recent work of Wahner et al. (*7*) has some data on the same spine segment as the present study regarding comparison of s.e.e. values. They found s.e.e.s in the range between 5% to 10% for excised vertebrae measured in vitro versus the actual BMC or

TABLE 4

Previous Studies on Accuracy of Lumbar Spine Bone Mineral Measurements by Dual Photon Absorptiometry

		Baseline/edge detection				Material used					
Study	Source	Computerized	Operator adjustment	Rst averaging	Transv. proc. incl.	Standards	In vitro versus ash weight	In vivo versus in vitro	L_2–4 segment	r	s.e.e. (%)
Judy PF et al., 1972	^{153}Gd	–	?	–	+		+		–	0.997	3
Wilson CR and Madsen M, 1977	^{153}Gd	–	?	–	+	+				0.99	1.2
Condon B et al., 1979 (abstract)	$^{241}Am/^{137}Cs$	?	?	?	?		+		–	0.98	?
Wahner HW and Dunn WL, 1980	^{153}Gd	+	?	+	?		+		–	0.99	?
Kølner B, Pors Nielsens, 1980	^{153}Gd	–	+	–	+	+				1.00	1.3
Wahner et al., 1985	^{153}Gd	+	+	+	–		+		–	0.94	10
	^{153}Gd	+	+	+	–		+		+	0.98	5.3
	^{153}Gd	+	?	+	?			+	+	0.995	4

BMD. The corresponding values in this study was also between 5% to 10%. BMD in situ versus BMD in vitro gave a s.e.e. of 4% in the study of Wahner et al. (7) compared to 8.4% for BMD and 5.2% for BMC in the present study.

This study is the first to disclose the correlation and accuracy error of spinal DPA measurements in situ in whole cadavers versus the actual BMC and BMD. The errors were 8.1% for BMC and 10.3% for BMD.

The errors of estimating the actual BMC or BMD from excised vertebrae scanned in vitro (i.e., in air or in various fluid mixtures or tissue equivalents) are between 5% and 10% in this and other studies. The errors of comparing in situ with in vitro measurements are between 4% and 9% in this and other studies. Comparing these values to the error of 8.1%–10.3% for in situ BMC and BMD versus actual BMC and BMD in excised vertebrae indicates that the total accuracy error of lumbar spine scanning is underestimated by giving values which include an in vitro measurement.

Comparison between in vitro and in situ measurements serve to stress the fact that the composition of extra- and intravertebral soft tissue (fat and lean) is an important component of the accuracy error. In an experiment of successive fat extraction, Wahner et al. (7) showed, that a change in 10% intraosseous fat gives an error of 0.6% in BMC.

We conclude that the accuracy error of going from in situ measurements of BMC and BMD in a group of mostly aged subjects to the actual BMC and BMD amounts to 10%.

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