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Original Article

Estimation of Bone Mineral Density by Digital X-ray Radiogrammetry: Theoretical Background and Clinical Testing

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Abstract. A new automated radiogrammetric method to estimate bone mineral density (BMD) from a single radiograph of the hand and forearm is described. Five regions of interest in radius, ulna and the three middle metacarpal bones are identified and approximately 1800 geometrical measurements from these bones are used to obtain a BMD estimate of the distal forearm, referred to as BMD_{DXR} (from digital X-ray radiogrammetry, DXR). The measured dimensions for each bone are the cortical thickness and the outer width, in combination with an estimate of the cortical porosity. The short-term in vivo precision of BMD_{DXR} was observed to be 0.60% in a clinical study of 24 women and the in vitro variation over 12 different radiological clinics was found to be 1% of the young normal BMD_{DXR} level. In a cohort of 416 women BMD_{DXR} was found to be closely correlated with BMD at the distal forearm measured by dual-energy X-ray absoptiometry ($r = 0.86$, $p < 0.0001$) and also with BMD at the spine, total hip and femoral neck ($r = 0.62$, 0.69 and 0.73, respectively, $p < 0.0001$ for all). The annual decline was estimated from the cohort to be 1.05% in the age group 55–65 years. Relative to this age-related loss, the reported short-term precision allows for monitoring intervals of 1.0 years and 1.6 years in order to detect expected age-related changes with a confidence of 80% and 95%, respectively. It is concluded that the DXR method offers a BMD estimate with a good correlation with distal forearm BMD, a low variation between geographical sites and a precision that potentially allows for relatively short observation intervals.

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Introduction

The diagnostic tools for evaluation of osteoporosis have changed considerably during the last 40 years. In the early 1960s radiogrammetry using in principle a plain radiograph and a simple ruler represented a major step forward [1], and later allowed also evaluation of structural features such as endosteal and periosteal resorption [2]. With the ever-improving possibilities of performing computerized image analysis of digital radiographs, radiogrammetry has attracted renewed interest. Several groups have used different approaches based on radiogrammetry [3–6] and the precision of the presented methods has gradually been improved.

Analysis of published radiogrammetric methods shows a great variety in the type of measurements that have been applied. Some techniques have focused on the combined cortical thickness (CCT) of a bone while others have used the metacarpal cortical index (MCI) or the inner diameter of the medullar space (ID). The utility of the different approaches has not been completely elucidated and the clinical use of the measurements has been impeded by the adopted use of bone mineral density (BMD) measured by dual-energy X-ray absorptiometry (DXA) as the gold standard.

The present paper describes a new radiogrammetric approach (digital X-ray radigrammetry, DXR) that from an assumed physical model of the bone attempts to bridge the gap between radiogrammetry and densitometry. This technique provides an estimation of BMD from basic geometric measurements, automatically

conducted in a single radiograph of the hand and forearm. Thus, the new radiogrammetric approach described here provides a BMD estimate as opposed to a traditional radiogrammetric quantity.

The theoretical background for the presented approach is described and the robustness of the new method is evaluated by in vivo and in vitro reproducibility studies. Finally, the paper aims to evaluate BMD_{DXR} in a cross-sectional cohort and to compare it with densitometry measurements at the forearm, lumbar spine, femoral neck and total hip.

Materials and Methods

To measure BMD using DXA, bone is projected onto a plane, a certain region of interest of the bone is identified and BMD is defined as the mineral mass of the bone projected onto this region, divided by the area of the region. Similar to the DXA technique, radiographic absorptiometry (RA) measures the attenuation of radiographs and compares this with an exposure standard included in the radiograph [7]. In contrast to both DXA and RA, radiogrammetry does not use the intensities of the image in a quantitative manner, but relies on geometric measurements. An exposure standard (e.g., an aluminum wedge) is therefore not needed.

The Basic DXR Methodology for a Single Bone

The fundamental radiogrammetric methodology of the DXR method is an automated segmentation of a given diaphysis into cortical and medullar regions (Fig. 1). This segmentation enables the measurement of an average cortical thickness and an average width of the bone over a given region of interest. The applied scanning resolution (300 dpi $\approx$ 5.5 lp/mm) enables the average thickness and the average width to be accumulated over approximately 118 individual measurements per centimeter along a given bone. For example, on the third metacarpal bone the measurement region is 1.70 cm long and the number of measurements contributing to the average bone width is therefore $1.70 \times 118 \approx 200$ (see also Table 1).

From the cortical thickness T and the outer width W of a bone, a compound measurement named Bone Volume per Area (VPA) is derived. Thus, while BMD by DXA involves the projection of bone *mass*, VPA is defined as the bone volume per projected area:

$$\text{VPA} = \text{Bone volume/Area}$$

Assuming that the bone of interest is cylindrical, the following simple equation holds exactly:

$$\text{VPA} = \pi \times T \times (1 - T/W)$$

As reported by Lazenby [8], the cross-sectional shape of the second metacarpal bone is elliptical rather than circular. This potential deviation from the circular assumption can explicitly be accounted for in the VPA formula by replacing the factor π with a general geometrical factor f:

$$\text{VPA}^* = f \times T \times (1 - T/W)$$

Using, for example, π times the eccentricity parameter of an elliptical shape as the factor f, this formula holds exactly for elliptical bones. For other shapes the alternative formula is approximate and the use of the formula then assumes that the bone shape is relatively constant across the population of interest. More specifically it is assumed that only the cortical thickness and width of the bone vary while the general shape is a constant. In practice, the constant f itself need not be determined separately since it is confounded with another multiplicative constant that subsequently relates VPA to BMD. Consequently, f is chosen to be equal to π.

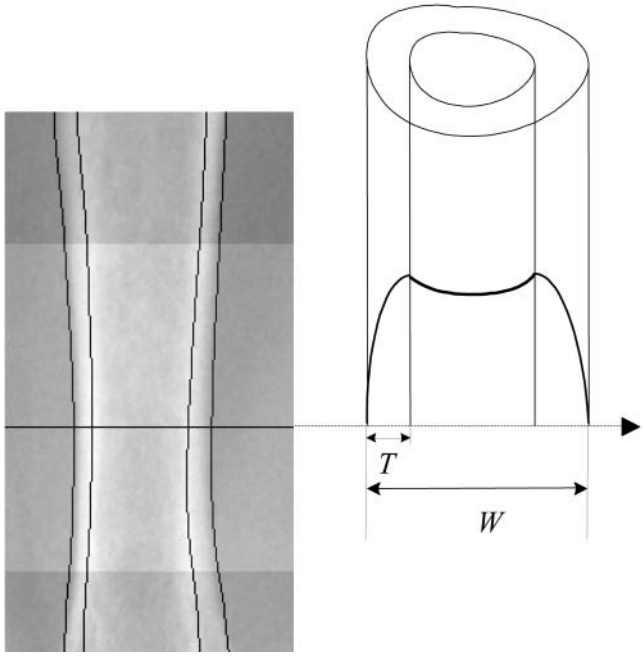

Fig. 1. The definition of the cortical thickness T and the bone width W. Shown is a cross-section of a cortical bone and the thickness profile of the bone when projected onto the film. The projection shows a characteristic shape with local maxima at the boundaries of the medullary region.

Table 1. ROI lengths and corresponding number of radiogrammetric measurements on the involved bones

Bone	ROI length (cm)	Number of width (W) measurements	Number of thickness (T) measurements
Metacarpal 2	1.9	225	450
Metacarpal 3	1.7	200	400
Metacarpal 4	1.5	175	350
Radius	5.0	590	590
Ulna	5.0	590	590

Note that only the outer cortices of radius and ulna contribute to the thickness measurements due to the wing-shaped aspects of these bones.

Thus, the noncircular generalization of the original simple VPA formula *is* implicitly adopted below.

The Use of Multiple Regions of Interest

As described above, VPA in a given single region of interest can be derived by a combination of the cortical thickness and the outer width of the contained bone. The precision and accuracy of such a single measurement can be improved by applying the described analysis to several bones and by averaging VPA over these bones, as suggested by Meema and Meindok [9]. To achieve the benefit of improved precision, the VPA analysis is applied to five bones in the hand and forearm and a combined VPA is calculated as a weighted average over these five bones. The referred bones are radius, ulna and the three middle metacarpal bones. The regions of interest (ROIs) used are shown as highlighted (white) areas in Fig. 2. These regions are automatically detected by the software and cannot be modified by the operator. The metacarpal ROIs are placed around the narrowest parts of the bone, while the ROIs of the radius and ulna are placed relative to a point where the distance between the intraosseous edges of radius and ulna reaches 4.0 mm. The lengths of the ROIs are given in Table 1, which also tabulates the total number of measurements that contribute to the average of a given variable (width and cortical thickness).

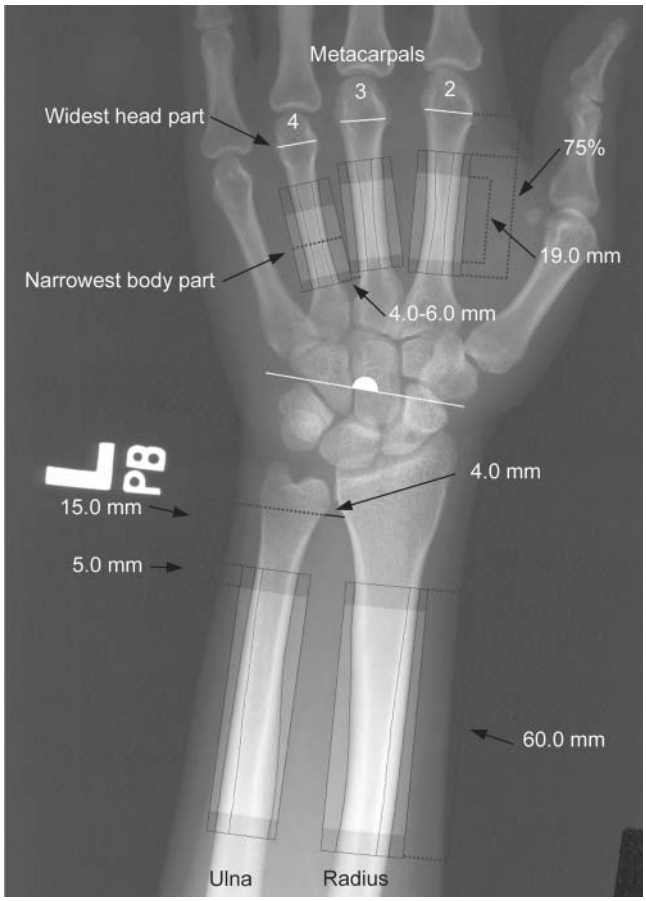

Fig. 2. The regions of interest used for calculations of VPA and BMD estimate are shown as the highlighted (*white*) areas. In the metacarpals, the cortical thickness is determined on both sides (radial and ulnar sides), while in the radius and ulna only the radial and ulnar sides respectively are used.

With regard to the metacarpal bones, both cortices contribute to the calculation of the cortical thickness of the bone. In comparison, only the lateral cortical part of radius and the medial cortical part ulna are used, since the wing-shaped aspects of these bones and the interference with the intraosseous membrane make these bone margins less well defined. The combined VPA over the five bones is derived according to the weighted formula:

$$VPA_{comb} = 0.5 \times ((VPA_{radius} + VPA_{ulna})/2 + (VPA_{met2}+VPA_{met3}+VPA_{met4})/3)$$

The implemented relative weighting of the individual VPAs implies that the average over radius and ulna and the average over the three metacarpal bones contribute equally to the combined VPA. The equal contribution provides maximal reduction of the measurement noise.

The DXR Formula

The DXR method links VPA to BMD via the universal proportional relation between the mass m of a homogeneous body and the volume V of the body: $m = \rho \times V$. In the context of BMD, ρ is the volumetric density of mineral matter in the bone. The mineral density reflects partly the degree of mineralization and partly the presence of cavities not occupied by mineral matter. Intracortical porosity seems to increase with age [10] but a positive trend with aging in the amount of highly mineralized bone has also been reported [11]. The mineral density was estimated by Laval-Jeantet et al. [10], who found it to be approximately constant when adjusting for porosities ($\rho \cong 1.2$ g Ca/cm^3). The standard deviation across individuals was close to 5%, including the measurement precision in the study. Thus, although there may be some individual variation in the volumetric mineral density ρ, the DXR method employs the fact that a good approximation to BMD may be obtained by multiplication of VPA by an appropriate constant.

The DXR method also involves a minor correction for porosities in cortical bone, which in parallel to the cortical thickness and the outer width of the bones is estimated from the image data. Porosity for each of the involved bones is derived from the area percentage (ratio) of local intensity minima (holes) found in the cortical part of the bone, relative to the entire cortical area. A combined porosity measure p is derived by averaging over the involved bones and by appropriate scaling to reflect a volumetric ratio rather than a projected (area) ratio. The scaling is conservatively chosen such that the combined measure p typically is less than 2%. The final BMD estimate (BMD_{DXR}) is effectively of the form:

$$BMD_{DXR} = c \times VPA_{comb} \times (1-p)$$

Table 2. Results of short-term in vivo precision (mean and range), calculated as suggested by Glüer CC et al. [12]

	Normal women (n = 11)	Osteoporotics (n = 13)	Total (n = 24)
Age (years)	66.8 (60–72)	72.9 (59–84)	70.1 (59–84)
Height (cm)	161.5	158.5	159.9
Weight (kg)	78.4	62.3	69.7
BMD mean (g/cm^2)	0.545	0.410	0.472
Repetition SD (g/cm^2)	0.0032	0.0024	0.0028
CV% (95% CI)	0.59 (0.42–1.00)	0.59 (0.43–0.95)	0.60 (0.47–0.83)

The marginally larger value of the total CV% than in the two age groups is true and due to the involved mathematics.

The applied value of the constant c has been empirically determined such that BMD_{DXR} on average is equal to that of the mid-distal forearm region of the Hologic QDR-2000 densitometer (Hologic, Waltham, MA). Data from 264 Caucasian American women sampled uniformly across an age range from 20 to 80 years was used in the calibration. The constant adapts VPA to both the volumetric mineral density of compact bone and the typical shape characteristics of the involved bones.

The DXR method is implemented in the X-Posure System (Pronosco A/S, Vedbaek, Denmark), which comprises a flatbed scanner, a desktop computer and a printer.

In Vitro Variability Study

In a clinical setting, radiographs are acquired under the influence of a range of potentially varying capture conditions, which by their variation could affect the precision of the measurement. To reveal the magnitude of such capture-induced variations in BMD_{DXR}, an in vitro study aiming at quantifying the measurement variation across different X-ray installations was performed. This study involved repeated measurements on an anthropomorphic phantom made of real bone molded in acrylic to simulate soft tissue. The bones of the phantom originated from a 83-year-old woman with a BMD_{DXR} of 0.320 g/cm^2. The phantom was sent to different radiological departments with a total of 12 different X-ray installations. A standard protocol was provided for acquisition of radiographs of the phantom. Three repeated radiographs with repositioning were made of the phantom at each of the 12 X-ray installations. A two-sided variance component model (ANOVA) was applied to analyze the data, i.e., both the repetition of X-ray capture and the variation in X-ray installations were assumed to induce stochastic variations of the measurements. The isolated contributions to the measurement variance by these two components were estimated.

Short-Term In Vivo Precision Study

For evaluation of the short-term in vivo precision, a study comprising 24 women with a mean age of 70.1 years (range 59–84 years) was carried out. According to BMD_{DXA} of the hip (measured by the Norland XR-26 densitometer; Norland Scientific Instruments, MZ Weesp, The Netherlands), 11 women were normal and 13 women had osteoporosis. More detailed demographic data are summarized in Table 2. All women had two radiographs of the nondominant hand and forearm taken with repositioning between the two. The film type was Agfa HT-L and a standard protocol was used for image capture. An individual standard deviation was calculated for each subject and a common pooled standard deviation was then derived as recommended by Glüer et al. [12]. The CV was subsequently calculated by division of the pooled standard deviation by the common mean.

Normative In Vivo Study

The data set used in a normative study was sampled among employees of Hvidovre Hospital (Denmark), the local population in the vicinity of the hospital and their relatives. The basic inclusion criterion was female sex in the age range 20–90 years. The following exclusion criteria were used: known bone disease including osteoporosis, history of malignancy within the last 5 years, previous stroke or myocardial infarction, known liver or kidney disease, or insulin-treated diabetes. Subjects treated with drugs known to affect bone metabolism and subjects with previous Colles' fracture of the nondominant forearm were also excluded. A questionnaire was filled out and subjects meeting these criteria were invited to participate. Individuals who turned out to have low bone mass were not secondarily excluded. Clinical data are summarized in Table 3. In addition to the acquisition of a radiograph of the nondominant hand and forearm, evaluation of BMD by DXA was performed using a Norland XR-26 densitometer (Norland Scientific Instruments). BMD was measured at the distal and ultradistal forearm, lumbar spine (L2–L4), femoral neck and total hip. For the forearm measurements the small subject software was used. The applied distal forearm region started 10 mm above (i.e., proximal to) the distal junction of the radius and ulna and extended 24 mm in the proximal direction. The ultradistal region was a region 10 mm wide just

Table 3. Clinical characteristics of study group

Age range (years)	*n*	Height (cm)	Weight (kg)	Age of last menstrual bleeding	BMD_{DXR} (g/cm^2)
20–29	73	167.3 (6.4)	66.0 (10.9)	–	0.578 (0.034)
30–39	78	167.4 (6.2)	66.9 (13.6)	–	0.592 (0.044)
40–49	69	166.4 (6.6)	68.3 (11.2)	45.4 (2.8)	0.592 (0.033)
50–59	55	164.0 (7.1)	72.9 (17.2)	48.9 (6.1)	0.544 (0.052)
60–69	60	161.0 (5.9)	70.1 (13.6)	49.5 (6.2)	0.487 (0.054)
70–79	49	160.0 (6.1)	67.4 (11.2)	48.8 (5.8)	0.446 (0.041)
80–90	22	155.9 (4.9)	58.5 (8.0)	48.9 (3.6)	0.396 (0.046)
Total	416	160.3 (7.0)	66.2 (13.0)	48.2 (5.8)	0.539 (0.076)

Values are mean (SD).

below (i.e., distal to) the distal forearm region. Thus, the ROIs differ somewhat in size and location from the ones used by the DXR method for radius and ulna. The distal forearm region obtained with the Norland XR-26 densitometer partly overlaps with the two regions used by the DXR method for radius and ulna.

The studies were carried out in accordance with the revised Helsinki Declaration (Somerset West 1996) and the protocol was approved by the local ethics committee. All participants received oral and written information before a written informed consent was obtained.

Results

In the in vitro study, the measurement error (standard deviation) caused solely by repetition of measurements within a fixed X-ray installation was found to be 2.65 mg/cm^2. In comparison, the error arising purely from the variation of sites amounted to 5.57 mg/cm^2. By combining these two quantities in quadrature the total reproducibility error was found to be 6.17 mg/cm^2, corresponding to approximately 1% of the mean BMD_{DXR} value of young adult women (0.600 g/cm^2 [13]).

The short-term in vivo precision study revealed a precision error of 0.60%, with the same precision among normal and osteoporotic subjects. These and other details of the study are outlined in Table 2.

In the normative study 416 women aged 20–90 years were included. This data set was used to correlate BMD_{DXR} with BMD_{DXA} of the distal forearm, spine and hip (see Table 5) and to compare cross-sectional age variation in the measurements. Since the algorithm is based upon equivalence to forearm BMD_{DXA} measured at the mid-radius using a Hologic QDR2000 densitometer, identical BMD levels were not expected when comparing BMD_{DXR} with the distal forearm BMD obtained with the Norland XR-26 scanner used in this study. To level out this difference, the latter measurement was divided by a scaling factor of 0.77. The correlation between the two measurements was $r = 0.864$ ($p < 0.0001$).

The SD for young normal women was significantly lower for BMD_{DXR} than for BMD_{DXA} of the distal forearm (0.041 vs 0.052 g/cm^2, $p < 0.001$). The variation with age in all the measured parameters demonstrated the expected significant decline with age (Fig. 3). Average annual changes have been estimated from the cohort for both BMD_{DXR} and for BMD_{DXA} of the distal forearm (Table 4). The observed annual decline in BMD_{DXR} with age was 0.81% for the age group 45–55 years and 1.05% for the age group 55–65 years. The corresponding values for BMD_{DXA} of the distal forearm were 0.79% and 1.37%, respectively. When adjusting the involved BMDs for SD of young normal women (Fig. 4), a somewhat steeper decline with age was seen for BMD_{DXR} compared with the BMD measurements by DXA.

The correlation between BMD_{DXR} and the available densitometric measurements from different sites varies in the range 0.62 to 0.96 (Table 5). With respect to central measurement sites of spine and hip, similar correlations for BMD_{DXA} of the distal forearm and BMD_{DXR} were seen. For distal forearm BMD the correlations were $r = 0.70$ and $r = 0.76$, respectively, and for BMD_{DXR} correlations of $r = 0.62$ and $r = 0.73$ were observed.

Discussion

Radiogrammetry is different in principle from bone densitometry, since it involves measurements of geometric dimensions (distances) while densitometry captures mineral densities. A higher spatial resolution is obtainable from digitized radiographs compared with the resolution of densitometry, allowing a better separation of cortical and trabecular regions together with better edge detection. Furthermore, radiogrammetry is not influenced by beam hardening and is insensitive to soft tissue thickness. This gives, at least in theory, radiogrammetry some advantages with respect to measuring cortical bone.

Following the initial work by Barnett and Nordin in 1960 [1], various improvements in the basic radiogrammetric methodology have been suggested, including averaging over multiple measuring sites on the same bone and averaging over several (metacarpal) bones [14]. The coefficient of variation (CV) has been reported

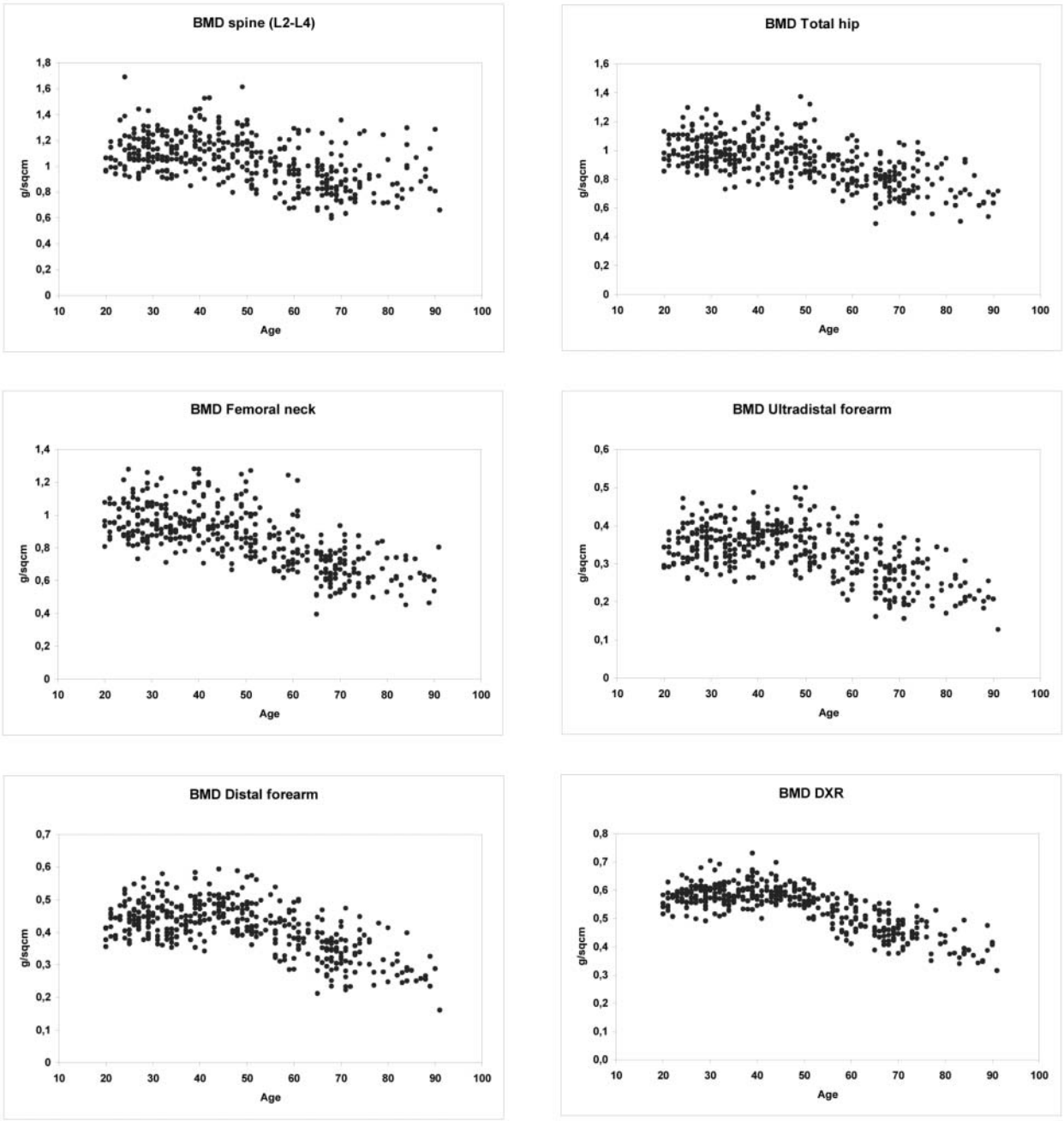

Fig. 3. Age variation in the 416 normal women.

Table 4. Estimated annual changes of both BMD_{DXR} and BMD_{DXA} of the distal forearm

Age group (years)	*n*	BMD_{DXR} (g/cm^2)	BMD_{DXA} (g/cm^2)	Annual change BMD_{DXR} (%)	Annual change BMD_{DXA} (%)
25 (20–29)	73	0.578	0.576	–	–
35 (30–39)	78	0.592	0.582	0.24	0.09
45 (40–49)	69	0.592	0.605	0.00	0.40
55 (50–59)	55	0.544	0.558	−0.81	−0.79
65 (60–69)	60	0.487	0.481	−1.05	−1.37
75 (70–79)	49	0.446	0.439	−0.84	−0.88

The annual changes are calculated as the relative difference between average BMD values in the current and in the previous age group.

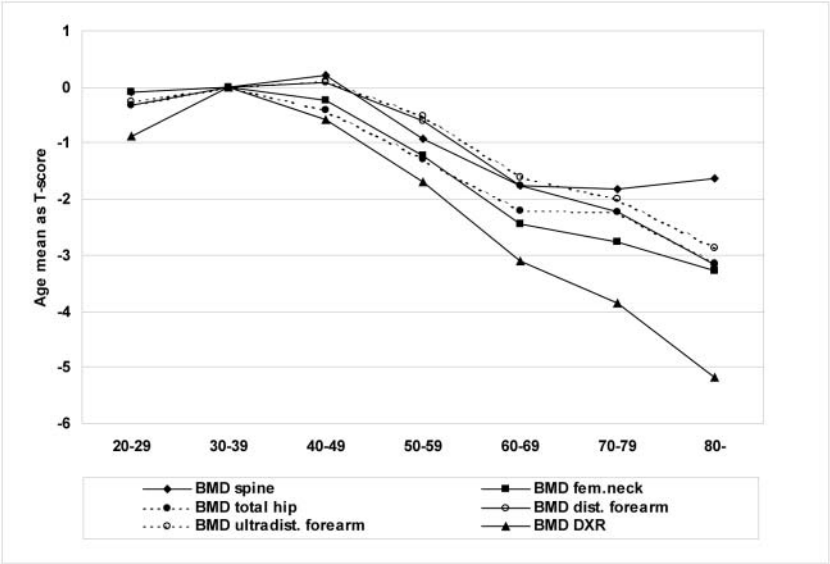

Fig. 4. Comparison of age variations expressed as *T*-scores of the age mean of each decade.

Table 5. Correlation (*R* values) between different DXA measurement sites and BMD_{DXR}

	BMD_{DXR} forearm + hand	BMD_{DXA} distal forearm	BMD_{DXA} ultradistal forearm	BMD_{DXA} femoral neck	BMD_{DXA} total hip
BMD_{DXA} spine	0.62	0.70	0.71	0.75	0.77
BMD_{DXA} total hip	0.69	0.76	0.76	0.93	–
BMD_{DXA} femoral neck	0.73	0.76	0.75	–	–
BMD_{DXA} ultradistal forearm	0.79	0.96	–	–	–
BMD_{DXA} distal forearm	0.86	–	–	–	–

All correlations are highly significant ($p < 0.0001$).

to be improved from approximately 11% for one measurement on a single metacarpal bone to 8.4% for the average over 9 measurements made on three metacarpal bones. An optical magnifier has been applied to provide a higher visual resolution [9,15]. Alternatively, others [16] have used digitally enlarged and displayed radiographs to improve the visual resolution of the analyzed radiograph. In that context, a CV of 2.4% has been reported. In recent years, the increasing computational ability of personal computers has enabled the development of computer-assisted radiogrammetric methods with varying degrees of automation. The reduced observer intervention has improved the CV to 1.5% and 0.89% as reported by and Adami et al. [5] and Derisquebourg et al. [4], respectively. When evaluating all the referred CV values it is important to note that in some instances they have been obtained from repeated measurements of a single radiograph for each participating individual, thereby ignoring the measurement variations arising from different capture conditions and body movement between repeated radiographs, etc. Only in the study by Adami et al. [5] a clear distinction between intra-radiograph and the inter-radiograph CV has been formulated and both values calculated. The inter-radiograph CV was reported to be 5.0% for the metacarpal index compared with 1.5% for the intra-radiograph CV. Table 6 gives a chronological overview of the type of precision that has been reported by the different publications.

The radiogrammetric approach presented here is based on digitized radiographs. Comparisons of BMD_{DXR} were made with BMD_{DXA} in a clinical setting, in which BMD_{DXR} was found to be highly correlated with BMD_{DXA} at all sites and also revealed an overall similar decrease with age (Table 4). When adjusting for the inter-individual variation, the decline in BMD_{DXR} with age became steeper than the decline in BMD_{DXA} (Fig. 4). The reported in vivo short-term precision study revealed a CV of 0.60%, which is substantiated by two later studies of BMD_{DXR} [17,18] using three repeated radiographs of 40 women and 20 women. These two other studies reported a CV of 0.65% and 0.66%, respectively.

When considering the clinical relevance of a typical short-term precision study, it is evident that it does not capture all the different sources of measurement noise that may influence measurements obtained over longer time intervals. Operator-dependent changes in the capture conditions and drift in the X-ray equipment will increase the measurement noise. Most of such random variations have been captured simultaneously by the in

Table 6. Repeatability of radiogrammetry measurements reported in the literature

Year	Author(s)	Measurement	Automation	CV (intra)	CV (inter)
1960	Barnett & Nordin [1]	MCI	Manual	–	7.25%
1960	Virtama & Mähönen [21]	CCT	Manual	1.6%	–
1983	Bloom [14]	CCT	Manual	8.4%	–
1989	Kalla et al. [3]	CCT	Computer-assisted	5.0%	–
1994	Matsumoto et al. [22]	MCI (Teijin)	Semi-automated	?	1.5%
1994	Derisquebourg et al. [4]	CCT	Semi-automated	0.9%	–
1996	Adami et al. [5]	MCI (Osteorad.)	Semi-automated	1.5%	5.0%
1997	Aguado et al. [16]	ID (Philips, CR)	Semi-automated	1.9%	?
1999	Jørgensen et al. [17]	BMD_{DXR}	Automated	–	0.65%
2000	Johnell et. al. [18]	BMD_{DXR}	Automated	–	0.66%
2000	Present study	BMD_{DXR}	Automated	(0.22%)[a]	0.60%

A question mark in a CV column indicates that it is not completely clear from the publication whether the reported CV represents an intra-radiograph CV or an inter-radiograph CV. Note that CCT refers to 2 times the average cortical thickness (CCT = 2T). ID denotes the inner diameter of a bone.

[a] The reported intra-assay CV of BMD_{DXR} was found in an internal technical (in vitro) study, using repeated scanning of the same radiograph.

vitro study, which evaluated the precision of BMD_{DXR} across different X-ray clinics, installations and operators. The magnitude of the variation in BMD_{DXR} induced thereby corresponded to approximately 1% of the mean BMD_{DXR} value of young adult women (0.600 g/cm^2 [13]). This variation is only moderately larger than the variation reflected by the pure short-term precision.

The reported CV% for BMD_{DXR} is lower than that normally reported for densitometric measurements. This characteristic observation is most likely explained by the automated procedure for identification of ROIs as well as the large number (approximately 1800) of individual radiogrammetric measurements contributing to each BMD estimate. The reported precision is of significance in relation to the expected longitudinal changes in BMD_{DXR}, for example due to disease progression or response to treatment. In order to be statistically significant at a 95% confidence level, an observed change over time must exceed 2.8 times the precision of the measurement [19]. If a confidence of only 80% is required, the change should be 1.8 times the precision. From these requirements and a certain expected change, the necessary monitoring intervals can be calculated. Using, for example, the estimated annual change of 1.05% for early postmenopausal women from 55 to 65 years of age (Table 4), the age-related change can be expected to be statistically significant after approximately 1.6 years ($\approx 2.8 \times 0.60/1.05$). Under the less strict requirement of 80% confidence, only 1.0 years ($\approx 1.8 \times 0.60/1.05$) is needed before the typical change becomes significant. It should be acknowledged that a potential difference between the long-term precision of BMD_{DXR} and the reported short-term precision implies some uncertainty of the estimated intervals. Nevertheless, these intervals are at least similar to those that have been reported for some BMD estimates based on DXA [19]. In the present normative study, the average annual change in the age group 55–65 years was estimated to be 1.37% for distal forearm BMD_{DXA}, which thus for that age group tends to decrease somewhat faster than BMD_{DXR}. To enable the same monitoring interval as for BMD_{DXR} (with 80% confidence) the precision of distal forearm BMD_{DXA} should be CV = $1.0/1.8 \times 1.37 = 0.78\%$.

With respect to evaluation of accuracy, a radiogrammetric method has inherently the same difficulties as densitometry and for both principles either biomechanical studies or longitudinal, prospective fracture studies are required to evaluate the accuracy. A potential additional limitation of the DXR method is its inability to account for changes in the degree of mineralization of the involved bones. The applied porosity estimation algorithm has a moderate precision and the conservative contribution of typically 2% is the result of a balance between the degree of contribution and the precision of the final BMD estimate. For the humerus porosity values of 4–12% have been reported [10] and the porosity contribution implemented in the DXR method therefore probably underestimates the true porosity. This potential inaccuracy undermines to some degree the assumed relation between VPA and BMD, but the impact seems to be minor as demonstrated by the relatively high correlations with forearm BMD_{DXA} reported here and by Black et al. [13]. The latter paper describes a reference study conducted in the USA, in which 564 women had BMD_{DXR} measured as well as distal forearm BMD_{DXA} by a Hologic QDR-2000 densitometer. Although the measurement regions of the two devices are different in both numbers and size, the correlation between the two BMD measurements was observed to be 0.90. In the present study, using a Norland densitometer and a somewhat different distal forearm region, a correlation of 0.86 was observed. The correlation with BMD_{DXA} in an ultradistal ROI was slightly lower ($r = 0.79$) This observation is in accordance with the findings of Derisquebourg et al. [4] and is probably explained by fact that the DXR method is based on the evaluation of cortical bone, which has a higher relative content in the distal ROI compared with the ultradistal ROI. Regarding the correlation with BMD at the hip and spine, BMD_{DXR} and BMD_{DXA} of the distal forearm revealed similar correlations.

Whether radiogrammetry will be able to match densitometry with respect to identification of individuals at risk of osteoporotic fracture is not yet fully known. A very high correlation between measurements from two different devices indicates that the same fracture prediction is likely. The DXR method shares the same potential limitation as, for example, forearm BMD_{DXA} of being a peripheral measurement, implying that some deviations from the skeletal status at axial measurement sites must be expected. To date, only limited data allow us to assess and compare DXA versus radiogrammetry, but Meema and Meema [20] have found radiogrammetry to be equivalent to DXA with respect to screening for osteoporosis. Black et al. [13] found similar relationships to fracture history of the hip for BMD_{DXR} and distal forearm BMD_{DXA}. Otherwise, the fact that BMD_{DXR} can be estimated with a high precision on radiographs without the need for specific film types or strict exposure settings and without the need for a reference wedge, potentially allows the opportunity of evaluating this measurement retrospectively, if previously taken radiographs of the forearm and hand are available. Thus, in that way a retroprospective design might give indications of the fracture prediction ability of the technique without a long follow-up period.

With the obvious need for identification of individuals at risk of osteoporosis and the ever-increasing public interest, the need for diagnostic facilities is still far from satisfied. DXA technology is useful in larger centers, but especially in areas with a less dense population patients would need to travel long distances for evaluation. In these settings, radiogrammetry or other techniques based on conventional radiographs are more convenient, since the readings and calculations can be performed centrally and the report returned to the local physician.

We conclude that the DXR method described constitutes a significant improvement on previous radiogrammetric approaches and brings the radiogrammetric methodology to a clinically applicable level. The presented properties of BMD_{DXR} support the idea that it may prove useful as an alternative to conventional densitometry by DXA.

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