Published in final edited form as:

J Clin Densitom. 2009 ; 12(3): 322–329. doi:10.1016/j.jocd.2009.05.002.

Correcting Fan-Beam Magnification in Clinical Densitometry Scans of Growing Subjects

Jacqueline H. Cole¹, Jodi N. Dowthwaite², Tamara A. Scerpella², and Marjolein C. H. van der Meulen^{1,3}

¹Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY

²Department of Orthopedic Surgery, SUNY Upstate Medical University, Syracuse, NY

³Research Division, Hospital for Special Surgery, New York, NY

Abstract

As children grow, body and limb girths increase. For serial densitometric measurements, growth increases the distance between the bone region of interest (ROI) and X-ray source over time, thereby increasing fan-beam magnification. To isolate bone accrual from magnification error in growing subjects we developed a correction method based on waist girth, a common anthropometric measure. This correction was applied to dual-energy X-ray absorptiometry (DXA) output obtained in a cohort of premenarcheal gymnasts and non-gymnasts. After correcting for magnification, results for projected area and bone mineral content (BMC) increased by 0.4–1.1% at the lumbar spine and 8–16% at the femoral neck, decreasing areal bone mineral density (aBMD) by 0.4–2.3% at both sites. The effects of magnification correction were similar in magnitude to BMC and aBMD gains previously reported in longitudinal studies of normoactive children. Due to body size differences, the effect of correction for BMC and aBMD was 10–20% greater in non-gymnasts than in gymnasts, which increased the observed aBMD differential between gymnasts and non-gymnasts. Fan-beam magnification distorts true changes in bone mineral measures in growing premenarcheal girls and, therefore, may obscure additional activity-related changes during growth. Our correction technique may enhance detection of skeletal adaptation, particularly in pediatric populations.

Introduction

Because bone accrual is rapid in growing subjects, clinical bone mineral measurements can increase significantly even over short time intervals. In dual-energy X-ray absorptiometry (DXA) studies of normoactive children aged 5–15 years, bone mineral measures increased substantially over 7–12 month intervals at both the lumbar spine and femoral neck. Specifically, bone projected area (Area, cm²) increased 0.1–13.4% (1–5), bone mineral content (BMC, g) increased 1.5–24.3% (1–9), and areal bone mineral density (aBMD, g/cm²) increased 1.2–7.4% (1,4–7,9–11). Growth-related gains were greatly enhanced by mechanical loading, resulting in accrual differentials up to 28 times larger for Area, 4 times larger for BMC, and 5 times larger for aBMD as compared to normoactive, age-matched controls (1,2,4–11).

Corresponding Author: Jacqueline H. Cole, Ph.D., Department of Chemistry, University of Michigan, 930 N. University Ave. Ann Arbor, MI 48109-1055, Tel/Fax: 734-763-0477, E-mail: jhc37@cornell.edu.

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Fan-beam densitometers are commonly used to assess bone mineral status. Compared to pencil-beam densitometers, these instruments are particularly practical in pediatric studies due to shorter scan times and higher spatial resolution. However, the configuration of the X-ray fan beam artificially magnifies bone mineral and geometric measurements by distorting linear measurements in the medial-lateral plane. Magnification occurs at a rate of 0.2-3.1% per centimeter change in height above the scanning table, resulting in a total variation of 1-37% in BMC and Area for height changes up to 20 cm (12-16). The magnitude of fan-beam distortion depends on the object distance from the X-ray source. Closer objects (i.e., bones of younger, smaller subjects with less soft tissue) appear to have a larger Area and higher BMC than the same objects positioned farther from the source (i.e., bones of older, larger subjects with more soft tissue) (Fig. 1). For clinical DXA scans, fan-beam magnification correction requires the quantification of scan distortion as a function of object distance from the X-ray source.

The distortion of DXA bone mineral measures by fan-beam magnification may obfuscate real changes, such as those associated with bone acquisition during growth or interventions (e.g., exercise and drug treatment). For most modern DXA scanners, the X-ray source is mounted beneath the scanning table. With this configuration, growth-related expansions in limb and trunk girths raise the distance (height) of bones above the X-ray source, erroneously decreasing bone mineral measures over time (Fig. 1). Girth changes in pre-pubertal girls can easily reach 3-5 cm (8-20%) per year at the thigh, corresponding to a change in height above the X-ray source of approximately 0.5-0.8 cm per year at the femur (17-19). Standardized data obtained using aluminum and anthropomorphic phantoms indicate that girth changes of these magnitudes would yield erroneous decreases of 0.8-2.5% per year for Area and BMC (12, 13). Errors of this magnitude are small, but they are comparable to reported changes in growing control subjects from the aforementioned loading studies (1-11). Thus, fan-beam error confounds normal growth-related changes in bone mineral measures and may obscure additional activity-related changes in growing subjects. To improve assessment of bone mineral gains associated with mechanical loading in growing subjects, a correction for the confounding effects of magnification error is necessary.

Previous studies have applied linear models to quantify magnification error in wide-angle fan-beam systems using cross-calibration data from pencil-beam systems (12,20-28) or reference data from animal models (29-31). One study used anthropometric measurements, such as hip circumference, height, weight, and body mass index, to correct fan-beam measurements of hip axis length (32). Our group previously investigated the use of a custom phantom to correct fan-beam magnification error in standard DXA output, including Area, BMC and aBMD (33). The phantom consisted of two aluminum rods of known geometry and density. One rod was positioned at table height, and the second rod was positioned at the approximate bone height as estimated by thigh girth. Fan-beam magnification was quantified by comparing the scanned projected rod width to the known rod diameter. This correction methodology proved problematic, as the custom phantom affected the identification of bone tissue by the system software, producing variable results for comparisons of scans with and without the phantom. Furthermore, the phantom could only be used in whole body scans, as the system software failed to recognize and analyze the phantom in other scans (e.g., hip and lumbar spine ROIs). Thus, we aimed to develop a correction method that would accurately quantify bone outcomes for clinically relevant regions of interest. The objectives of our study were 1) to develop an analytical correction for DXA magnification error based on common noninvasive measures and 2) to determine the effect of this correction on bone mineral measures in a cohort of premenarcheal gymnasts and non-gymnasts (17-19).

Materials and Methods

The development of a correction technique for fan-beam magnification error was a multi-step process. First, we used a series of computed tomography (CT) scans from normal children to determine an anatomical relationship between body size and bone height above the DXA table (ROI height) for two regions of interest: lumbar spine (LS) and femoral neck (FN). Waist girth and ROI height were measured digitally, and linear regression models were used to determine the relationship between the two measures. Second, we used DXA scans of a custom phantom to quantify the relationship between ROI height and DXA magnification error for Area, BMC and aBMD measurements, generating linear regressions for each measure. Finally, to assess the effect of this correction approach, we used our own DXA data from a cohort of growing gymnasts and non-gymnasts (17-19). A subset of these DXA scans was corrected analytically, as follows. Waist girth measurements from each subject were used to estimate ROI height at the LS and FN by applying the regression equations generated from the CT data. In addition, the phantom regressions were used to calculate the magnification error in each DXA measure for these ROI heights, and on this basis, corrected output were generated for Area, BMC, and aBMD at the LS and FN. Corrected and uncorrected data were compared to determine whether the correction resulted in a significant alteration of study outcomes. Each step of the correction procedure is detailed below.

CT-Based Anatomic Relationships in Normal Subjects

Because the gymnast study protocol did not include CT scans, we used existing abdominal CT scans from a separate cohort to determine the relationship between waist girth and ROI height. Using a digital database of radiographic studies at an affiliated hospital, we obtained CT scans from a cohort of 16 girls (CT cohort) ages 3-18 years (mean age = 12.2 ± 4.7 years), which encompassed the age range of our gymnasts and non-gymnasts. No information about the menarcheal status of the CT cohort was available in the database. CT scans were evaluated for waist girth (a measure of body size) and ROI height (skeletal height above the scanning table, a measure of location within the DXA fan beam) at two clinically relevant regions, the LS and FN. Waist girth and ROI height were measured digitally using the ruler functions in standard image analysis software (Synapse®, version 3.1.1, FUJIFILM Medical Systems USA, Stamford, CT). A single investigator performed all ruler measurements.

CT-derived waist girth was examined in the coronal slice immediately superior to the iliac crest (Fig. 2). This cross-section was analogous to the position used to measure waist girth in our gymnast study. Waist girth could not be measured directly with the CT image analysis software; instead, the body cavity was approximated as an ellipse by tracing the perimeter and measuring the body width and thickness. The ellipse major radius (a) was defined as half the body width, and the minor radius (b) was defined as half the body thickness. Waist girth was calculated as the ellipse circumference using the Ramanujan approximation (34), as follows:

$$\text{waist girth}_{\text{CT}} = \pi \left(3a + 3b - \sqrt{(a+3b)(3a+b)} \right) \quad (1)$$

This procedure was repeated three times per subject, and the mean waist girth was used in subsequent analyses.

To measure ROI height for the LS and FN regions, a horizontal reference was digitally superimposed across the concave surface of the CT scanning table using the analysis software. ROI height measurements were made perpendicular to this reference, corresponding to measurements made on a flat DXA scanning table. In the CT scans, LS ROI height was evaluated in a coronal slice that contained the inferior region of the 3rd lumbar vertebra (L3)

or, if L3 was not clearly visible, the superior region of the 4th lumbar vertebra (L4). LS ROI height was measured vertically from the horizontal reference line to the center of either L3 or L4 (Fig. 3a). FN ROI height was assessed in the coronal slice where both left and right FN sections were clearly visible and had circular cross-sections. The heights were measured from the horizontal reference line (table top) to the centers of the left and right FN sections (Fig. 3b). FN ROI height was recorded as the mean of the left and right FN heights. Measurements for LS and FN ROI heights were made three times, and the mean values were used in all subsequent analyses. The relationship between mean ROI height (LS and FN) and mean waist girth was assessed in the CT cohort using simple linear regressions (SAS 9.1, SAS Institute Inc., Cary, NC). A significance level of 0.05 was used in all analyses.

Variation of Magnification with Height above the Scanning Table

The height-dependent variation in fan-beam magnification error for Area, BMC, and aBMD was determined using a custom phantom scanned over a range of heights above the table surface (33). The custom phantom consisted of a solid Plexiglas® block configured with holes to support aluminum rods (diameter 2.50 cm) of identical geometry and density. A single hole on the right side of the block allowed placement of an aluminum rod at table height. Multiple holes, stacked vertically on the left side of the block, were positioned at 1.75, 5.25, 8.75, 12.25, and 15.75 cm above the scanning table (Fig. 4). The aluminum rods were used to simulate a cylindrically-shaped bone, and the Plexiglas® material mimicked the presence of soft tissue. For each set of scans, an aluminum rod was placed at a selected height, and the other heights were filled with Plexiglas® rods to prevent beam hardening from passage of the X-ray beam through air. A second aluminum rod was placed in a fixed position at the table surface in the right column. The phantom was centered and aligned on the DXA table so that the right column was closest to the operator. Using the lumbar spine fast array mode, the phantom was scanned eight times for each rod height, with repositioning between scans (Hologic QDR 4500W, Bedford, MA). Each scan was analyzed for Area, BMC, and aBMD of the aluminum rod at the variable heights above the table. The data for the fixed aluminum rod in the right column were used only for reference. The relationship between magnification of DXA measures and rod height above the scanning table was examined using simple linear regression, generating separate equations for each bone outcome (Area, BMC, and aBMD).

Analytical Correction for Gymnast Study Data

As described below, a geometric correction for fan beam magnification error was derived based on 1) the relationship between ROI height and waist girth (from the CT cohort) and 2) the relationship between magnification of DXA measures and rod height (from the phantom scans). The effect of magnification correction was evaluated in a cohort of 56 premenarcheal girls (28 gymnasts, 28 non-gymnasts) aged 8-13 years who had undergone scans on the same Hologic QDR 4500W scanner used for the phantom scans. These subjects were participants in an existing longitudinal study (17-19) and were included in the present analysis if they reported either self-assessed Tanner stage I for both breast and pubic assessments or Tanner stage II for both assessments coincident with DXA scanning (35). This narrow maturity range was selected to minimize the effect of maturation as a confounding factor in bone mineral accrual, simplifying data interpretation. Lumbar spine and hip DXA scans were analyzed for Area, BMC, and aBMD at L2 (2nd lumbar vertebra), L3, and FN. Anthropometric data, including waist girth, were recorded at the time of the DXA scans.

For each gymnast and non-gymnast, the LS and FN ROI heights were estimated from the girl's waist girth, based on the CT-derived regressions, as follows:

$$\text{height}_{\text{uncorrected}} = \text{intercept}_{\text{CT}} + \text{slope}_{\text{CT}} * (\text{waist girth}) \quad (2)$$

where $\text{intercept}_{\text{CT}}$ and slope_{CT} correspond to the site-specific CT regression components and waist girth is the measured value for that girl.

Next, DXA bone mineral measures for each subject (Area, BMC, aBMD) were corrected for magnification at the LS and FN using the formula for the slope of the phantom regressions, $\text{slope}_{\text{phantom}}$, as follows:

$$\text{measure}_{\text{corrected}} = \text{measure}_{\text{uncorrected}} - \text{slope}_{\text{phantom}} * (\text{height}_{\text{corrected}}) \quad (3)$$

$\text{Measure}_{\text{uncorrected}}$ was the value of Area, BMC, or aBMD obtained from the standard DXA analysis. $\text{Measure}_{\text{corrected}}$ was defined as the value of Area, BMC, or aBMD that would be obtained if the object was scanned at a position with zero magnification, which we defined as the assumed bone height used in the scanner analysis software ($\text{height}_{\text{zero}} = 5.08$ cm).

$\text{Height}_{\text{corrected}}$ was obtained by subtracting $\text{height}_{\text{zero}}$ from $\text{height}_{\text{uncorrected}}$, which was estimated using the CT-derived regression and measured waist girth, as described above.

Effect of Correction on Gymnast Study Data

The effect of the geometric correction on the gymnast study data was investigated by comparing corrected and uncorrected Area, BMC, and aBMD using paired t-tests. In addition, percent differences were assessed between corrected and uncorrected measurements as follows:

$$\% \text{Diff} = \frac{\text{measure}_{\text{corrected}} - \text{measure}_{\text{uncorrected}}}{\text{measure}_{\text{uncorrected}}} \times 100 \quad (4)$$

The effect of group (gymnasts, non-gymnasts) on these differences was assessed using a one-way analysis of variance (ANOVA).

Results

CT-Based Anatomical Relationships in Normal Subjects

For the CT cohort, the width of the body cavity measured 16.4-33.2 cm (mean = 26.4 ± 5.5 cm), and the thickness measured 13.4-22.5 cm (mean = 17.7 ± 2.5 cm), yielding a body cavity aspect ratio of 0.55-0.85 (mean = 0.68 ± 0.09). Mean waist girth, calculated as the circumference of the approximating ellipse, was 46.8-85.8 cm (overall mean = 70.9 ± 13.1 cm). Mean lumbar spine ROI height measured 4.5-8.8 cm (overall mean = 6.8 ± 1.5 cm), and mean femoral neck ROI height was 5.0-11.1 cm (overall mean = 8.6 ± 2.1 cm). Mean LS and FN ROI heights increased linearly with increasing mean waist girth ($p < 0.0001$ for both, $r^2 = 0.94$ and 0.96 , respectively), with regression equations as follows (Fig. 5):

$$\text{LS height}_{\text{CT}} = -1.38 + 0.12 * (\text{waist girth}_{\text{CT}}) \quad (5a)$$

$$\text{FN height}_{\text{CT}} = -2.75 + 0.16 * (\text{waist girth}_{\text{CT}}) \quad (5b)$$

Variation of Magnification with Height above the Scanning Table

Analysis of the custom phantom results demonstrated a decrease in both Area and BMC as rod height increased ($p < 0.0001$ and $p = 0.003$, respectively, Fig. 6). Because the slopes of these two regressions were similar, aBMD did not vary significantly with rod height, although it tended to increase ($p = 0.055$). The variability in the data was generally large. Rod height explained 74% of the variability in Area, 21% in BMC, and only 9% in aBMD. The phantom regression equations were as follows:

$$\text{Area}_{\text{phantom}} = 13.10 - 0.19 * \text{height}_{\text{phantom}} \quad (6a)$$

$$\text{BMC}_{\text{phantom}} = 19.60 - 0.21 * \text{height}_{\text{phantom}} \quad (6b)$$

$$\text{aBMD}_{\text{phantom}} = 1.48 + 0.01 * \text{height}_{\text{phantom}} \quad (6c)$$

Analytical Correction for Gymnast Study Data

For gymnasts and non-gymnasts, measured waist girth was 50.0-80.7 cm (mean = 59.8 ± 6.1 cm). Substituting these girth values and the CT regression intercepts and slopes from Eq. 5a-b into Eq. 2 yielded estimated LS ROI heights of 4.5-8.1 cm (mean = 5.6 ± 0.7 cm) and FN ROI heights of 5.4-10.3 cm (mean = 6.9 ± 1.0 cm). This procedure provided the uncorrected heights used to correct the DXA magnification error for each subject at both regions of interest (Eq. 3). For each subject, FN ROI heights were 0.9-2.3 cm (mean = 1.3 ± 0.3 cm) greater than LS ROI heights. Compared to the uncorrected values, corrected Area and BMC increased, and aBMD decreased, at the LS and FN for gymnasts and non-gymnasts ($p < 0.001$, Table 1).

Effect of Correction on Gymnast Study Data

At the spine, corrected DXA values were 0.4-0.7% larger for Area, 0.6-1.1% larger for BMC, and 0.4-0.8% smaller for aBMD than uncorrected values for gymnasts and non-gymnasts. Compared to the spine, increasing FN ROI height resulted in greater differences between corrected and uncorrected data for all DXA measures. Mean FN area increased by 8.0-9.6%, BMC increased by 12-16%, and aBMD decreased by 1.7-2.3% in gymnasts and non-gymnasts. The percent difference between corrected and uncorrected data was larger in non-gymnasts than gymnasts at the FN for both BMC (16.0% vs. 12.1%, $p = 0.04$) and aBMD (-2.3% vs. -1.7%, $p = 0.02$). A similar trend was observed for BMC and aBMD at the LS, although these results were not significant. For Area, the differences in correction between gymnasts and non-gymnasts were not significant at either the LS or FN.

Discussion

Fan-beam magnification affected clinical bone mineral measurements in this premenarcheal cohort of gymnasts and non-gymnasts, especially at the femoral neck. Our analytical correction technique increased values for Area and BMC at the lumbar spine and femoral neck, thereby decreasing aBMD at both sites. The impact of the correction was much greater at the FN than at the LS, because the FN was located at a greater distance above the assumed zero magnification position (FN height: 1.9 ± 1.0 cm; LS height: 0.5 ± 0.7 cm). Of note, the percent changes resulting from magnification correction were within the range of values reported in previous longitudinal studies of normoactive children for BMC and aBMD accrual over 7-12

months at the LS (1-18%) and aBMD accrual at the FN (2-12%) (1,3-11,36). Subjects in the intervention groups of these longitudinal studies had between 5% lower and 20% higher aBMD at both the LS and FN (1,4-7,9-11,17-19,36-43). These values lie within the magnification correction range of the present study, highlighting the potential problem with interpreting axial DXA data that are not corrected for fan-beam magnification.

On average, non-gymnasts' ROI heights were greater than gymnasts' ROI heights (LS = 5.8% greater, FN = 6.5% greater). At both sites, the magnification correction effect was 1.3-2.1 times greater in non-gymnasts than gymnasts for BMC and aBMD data. Compared to gymnasts, non-gymnasts exhibited smaller uncorrected aBMD and relatively larger reductions in aBMD due to correction. Therefore, the difference in aBMD values between gymnasts and non-gymnasts was greater after magnification correction, increasing the observed gains associated with mechanical loading. In contrast, because correction increased BMC more in non-gymnasts than in gymnasts, BMC differentials were reduced by correction, thereby diminishing observed loading gains. Magnification correction did not alter Area differences between gymnasts and non-gymnasts in our cohort. To date, our correction algorithm has only been applied in premenarcheal subjects within a limited body size range. Studies evaluating larger body size differentials, as might occur in later pubertal stages or over longer inter-measurement intervals, may demonstrate an even greater magnification influence.

Bone height was estimated for gymnast and non-gymnast DXA scans using waist girth, a simple metric that has been collected throughout our ongoing study. In the CT cohort, waist girth was highly predictive of the LS and FN ROI heights, explaining 94-96% of the variability in the CT data for normal female children and adolescents. Although the menarcheal status of the CT cohort was unknown, the high correlation between waist girth and ROI height indicate that this relationship holds across a broad range of ages and pubertal stages. Measured waist girths for gymnasts and non-gymnasts ranged between 50 and 81 cm, which fell within the range of CT-computed waist girths (47-84 cm). Ideally, our assessment of the relationship between waist girth and ROI height would have been performed in subjects from the gymnast study near the time of their DXA measurements. However, CT scans were not part of that study protocol and, more importantly, would have increased radiation exposure to the subjects. A future study using contemporaneous DXA scans and magnetic resonance imaging to evaluate the use of waist girth in estimating bone height would be useful to validate our methodology. Similarly, the use of contemporaneous DXA scans and quantitative CT (QCT) scans would allow comparison of corrected aBMD and QCT-measured volumetric BMD.

ROI height could have been predicted using hip girth rather than waist girth, as done in a previously published study that predicted hip axis length with high accuracy (32). However, in our study, most of the pelvic CT scans excluded a portion of the body envelope from the field of view, preventing accurate measurement of hip girth. In addition, preliminary hip girth measurements taken from the subset of scans with a fully-visible body envelope correlated well with LS ROI height but poorly with FN ROI height. Waist girth correlated well with ROI height at both sites and provided a superior metric for this application.

The custom phantom used for this study was questionably anthropomorphic, which may have affected study findings. However, the aluminum rods were designed to mimic the geometry and density of long bones. The measured BMC for the aluminum rods was 7-23 g over the ROI height range examined, which was similar to the 7-21 g for the LS and 2-4 g for the FN observed in gymnasts and non-gymnasts. Despite the anthropomorphic assumptions built into the scan and analysis software, the edges of the aluminum rods were consistently and accurately detected. We plan to utilize anthropomorphic phantoms in future validation studies of our correction algorithm.

The height range of the custom phantom (1.75-15.75 cm) included the estimated LS and FN ROI heights for the gymnast data (4.5-8.1 cm and 5.4-10.3 cm, respectively). Although both Area and BMC decreased with rod height in phantom scans, the regression slopes were similar (-0.19 and -0.21, respectively). The relatively low predictive value of rod height for BMC variation ($r^2=0.21$) may have resulted from the high measurement variability, suggesting that positional variation may be an additional factor in BMC measurement over this height range. In contrast, rod height was a stronger predictor of Area ($r^2=0.74$), with lower measurement variability. Not surprisingly, aBMD, computed as the ratio of Area to BMC, did not vary significantly with rod height.

The correction algorithm was applied assuming that zero magnification occurs at a height of 5.08 cm above the scanning table, the assumed height used in the analysis software of our DXA system. To our knowledge, no study has investigated the validity of this assumption. In one study using the Lunar Expert scanner, the measured width of an aluminum phantom matched the actual width when the scanning table was raised 10.7 cm above the normal scanning position (14). Using a similar tactic, our methodology employed simple regressions to adjust the bone measures to their predicted values at a height where magnification should be minimal (5.08 cm). Future work will validate this assumption by determining the exact location of minimal magnification for our DXA system.

In conclusion, fan-beam magnification alters DXA bone mineral measures at the spine and hip in premenarcheal gymnasts and non-gymnasts and may obfuscate genuine changes associated with growth or mechanical loading. We used waist girth to estimate the height of FN and LS ROIs within DXA scans to correct for this magnification effect. For our cohort, the magnification correction *decreased* observed group differences in BMC; consequently, in previous exercise or loading studies using fan-beam DXA, BMC gains may have been overestimated. In contrast, the correction *increased* group differences in aBMD. Therefore, our method for correcting fan-beam magnification in DXA scans may improve detection of aBMD adaptation in growing subjects.

Acknowledgments

The authors would like to thank University Hospital in Syracuse, NY, for use of their CT database. We are also grateful to David Barnwell (Department of Radiology, SUNY Upstate Medical University) for his assistance with CT scan analyses. This work was funded by the National Institute of Arthritis and Musculoskeletal and Skin Diseases (R03-AR47613), and bridge grants from SUNY Upstate Medical University. JHC acknowledges support from NIAMS (T32-AR007281) and the American Association for University Women Educational Foundation (Selected Professions Fellowship).

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Fig. 1.

A bone that is positioned closer to the surface of the scanning table (height H_1), and hence to the X-ray source, will experience a wider fan-beam angle and thus will be seen by the detector array as having a larger diameter D_1 (and, incidentally, larger Area and BMC) than a bone that is farther from the source (D_2 at height H_2).

Fig. 2.

Coronal slice located immediately superior to the iliac crest was taken from an abdominal CT scan. Waist girth was computed by approximating the body cavity as an ellipse. Width and thickness of the cavity were measured using standard CT scan analysis software, and waist girth was defined as the circumference of the approximating ellipse defined by these measures (Eq. 1).

Fig. 3.

ROI height was estimated using coronal slices of CT scans evaluated at (a) the inferior region of L3 or superior region of L4 for the lumbar spine (h_{LS}) and (b) the location where both right and left femoral neck regions appeared most cylindrical (h_{FN}).

Fig. 4.

Custom phantom to measure fan-beam magnification in clinical bone density scans made of a solid Plexiglas® block with two columns of holes cut parallel to the table surface. One round aluminum rod was placed at the scanning table surface in the column on the right, and another rod was placed at one of five different heights above the table in the column on the left. ϕ = diameter.

Fig. 5. Lumbar spine and femoral neck ROI height increased linearly with waist girth for a cohort of adolescent girls measured using CT scans ($p < 0.0001$). Regression equations and coefficients of determination are listed, where y = ROI height and x = waist girth.

Fig. 6.

Area and BMC decreased linearly with rod height for a custom phantom scanned eight times at each height using DXA ($p < 0.0001$). Regression equations and coefficients of determination are listed, where y = either Area or BMC and x = rod height. Points are mean value at that height $\pm$ standard deviation.

Table 1

Uncorrected (Uncorr) and Corrected (Corr) Values and Percent Differences (% Diff) for Area, BMC, and aBMD at the Lumbar Spine (LS) and Femoral Neck (FN) in Premenarcheal Gymnasts and Non-gymnast Controls

Measure	Gymnasts (n = 28)			Non-gymnasts (n = 28)			ANOVA p-value
	Uncorr	Corr	% Diff	Uncorr	Corr	% Diff	
LS Area (cm ²)	19.24 (2.04)	19.32 [†] (2.04)	0.39 (0.47)	19.28 (2.78)	19.41 [†] (2.83)	0.66 (0.83)	0.1278
LS BMC (g)	14.03 (2.88)	14.11 [†] (2.91)	0.59 (0.74)	12.72 (3.21)	12.86 [†] (3.25)	1.14 (1.48)	0.0831
LS aBMD (g/cm ²)	0.723 (0.089)	0.721 [†] (0.088)	-0.40 (0.48)	0.652 (0.088)	0.647 [†] (0.087)	-0.82 (1.07)	0.0616
FN Area (cm ²)	3.87 (0.35)	4.18 [‡] (0.40)	7.96 (3.13)	4.03 (0.36)	4.42 [‡] (0.50)	9.56 (5.18)	0.1683
FN BMC (g)	2.84 (0.43)	3.18 [‡] (0.50)	12.12 (4.55)	2.70 (0.41)	3.13 [‡] (0.56)	15.96 (8.54)	0.0405 [*]
FN aBMD (g/cm ²)	0.731 (0.078)	0.719 [‡] (0.076)	-1.69 (0.62)	0.668 (0.066)	0.652 [‡] (0.065)	-2.34 (1.35)	0.0231 [*]

Values listed as mean (SD)

Corrected value differed significantly from uncorrected value ([†] p < 0.001, [‡] p < 0.0001)

Non-gymnasts > Gymnasts for |% Diff| (* p < 0.05)