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Original Article

The Effect of the Lumbar Vertebral Malpositioning on Bone Mineral Density Measurements of the Lumbar Spine by Dual-Energy X-Ray Absorptiometry

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Abstract

A significant discrepancy between the results of previous human and phantoms studies is identified regarding the effects of vertebral positioning on bone mineral density (BMD) measurements. We aimed to evaluate the effects of lumbar vertebral positioning on BMD measurements by dual-energy X-ray absorptiometry in a human cadaveric spine phantom. A spine phantom was designed using L1–L4 vertebrae harvested from a 48-year-old male cadaver without coronal or sagittal deformity. The spine phantom was scanned by DEXXUM T bone densitometer in a constant scanning speed of 30 mm/s and resolution of 1.0×1.0 mm. BMD values were measured in a positive and negative lumbar lordosis and kyphosis tilt angles in the sagittal plane, from 0° to 35°, with 7° increments. Also BMD values were measured in axial and lateral rotations with 5° increments. Projectional dual-energy X-ray absorptiometry measurements are significantly affected by positioning of the lumbar spine, more severely affected by kyphotic curvature, but also by axial and lateral rotational scoliosis as well as lordotic curvature. Increasing the severity of lordosis and kyphosis curvatures leads to false reduction of BMD value up to 17.5% and 11.5%, respectively. Increasing the degree of lateral and axial rotational scolioses results in a false decrease in BMD measurements by up to 10.8% and 9.6%, respectively. To achieve the most accurate scanning results, error sources and abnormal positioning should be identified and minimized as much as possible. If not correctable, they should be taken into consideration while interpreting the results.

Key Words: Absorptiometry; bone malposition; densitometry; DXA scan; scoliosis

Introduction

Osteoporosis is by far the most common metabolic bone disease, mainly involving the older population. As osteoporosis is generally an asymptomatic disease, bone mineral density (BMD) measurements have been widely employed as the main screening and diagnostic tool. Previous studies have shown that BMD values are inversely associated with the risk of pathological fractures *(1–3)*. Accordingly, BMD values have been directly translated and incorporated to the management algorithms and guidelines of osteoporosis, which emphasizes on the importance of accurate measurement of BMD for appropriate management of these patients.

Dual-energy X-ray absorptiometry (DXA) is the most commonly employed imaging technique to evaluate for osteoporosis and has been considered as the most cost-effective method for BMD measurements. However, this method is known to have some limitations and its BMD values are affected by several confounding factors *(1,4)*.

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Most importantly, DXA is a projectional technique that lacks the potential for bone volumetric demonstration. It is mainly dependent on 2-dimensional coronal surface area measurements on coronal planes and bone mineral content (BMC) evaluation by differential absorption of 2 different photon energies. Therefore, any osseous deformity and abnormality that affect projectional presentation of the osseous structures on the coronal plane can potentially affect the output of BMD measurements *(3)*. For example, this is true for scoliosis or any type of axial/lateral rotation or lordosis/kyphosis curvature of the lumbar spine in case of lumbar spine BMD measurements. Also, in BMD measurements by DXA, the most important source of error has been reported to be improper positioning of the patient *(5–9)*.

A significant discrepancy between the results of human studies and phantom models is identified, with phantom studies suggesting decreased BMD measurements as the rotation angle increases *(3,5)* and human studies reporting increased BMD with scoliosis *(6,7)*. Therefore, development of a phantom that audits the accuracy of simulation is becoming increasingly more important. In the present study, we aimed to evaluate the effects of lumbar vertebral positioning on BMD measurements by DXA in a human cadaveric spine phantom.

Material and Methods

In the current study, we designed a spine phantom using L1–L4 vertebrae harvested from a 48-year-old male cadaver without coronal or sagittal deformity. All soft tissues were removed and the harvested spine was embedded in a rectangular water phantom with a dimension of $50 \times 30 \times 30$ cm^3. Each vertebral body was fixed in a plastic stand within the water phantom, which was specifically developed for positioning the specimens. The plastic stand was equipped with markings calibrated with the degree of rotation from the neutral midline position. Both posterior tips of the lumbar spine facets were placed in contact with the vertical part of the plastic stand.

The spine phantom was scanned by DEXXUM T (Osteosys Co., Ltd., Seoul, South Korea) bone densitometer in a constant scanning speed of 30 mm/s and a resolution of 1.0×1.0 mm. The BMC and biplanar vertebral segment area of each lumbar vertebral body as well as L1–L4 lumbar segments were measured to calculate BMD. The BMC, area, and BMD values are measured in gram, square centimeter, and gram per square centimeter, respectively. These values were evaluated with the spine in the midline nonrotated, nonangulated neutral position, true anteroposterior projection, which was achieved by laying the L2–L4 vertebral bodies horizontally on the plastic stand. Subsequently, to evaluate variations of BMD with respect to variations in lordotic and kyphotic curvatures, the abovementioned values were measured in a wide range of positive and negative lumbar lordosis tilt angles solely in the sagittal plane, from 0° to 35°, with 7° increments compared to the ex-position using Cobb's method *(8)*. For axial rotation, each vertebra was glued on a prepared plastic stand (with the same height) fixed on a plastic plate in the water phantom. Axial rotation angles were created from 0° to 30° with 5° increments. Finally, to evaluate variations of BMD with respect to variations in lateral scoliotic curvatures, the same values were measured in a wide range of lateral tilt angles solely in the coronal plane, from 0° to 45°, with 5° increments.

To reduce the possible errors in region of interest positioning, all region of interest selections and measurements were performed by the same scientist. The quality control procedure was performed before measurements as per guidelines of the manufacturer and the precision error was set at 1%.

Statistical Analysis

All DXA readings for each neutral and tilted/rotated positions were repeated 3 times and average measurements were recorded to minimize the effect of technical or statistical errors on the results. The mean and coefficient of variation for DXA measurements of each neutral and tilted/rotated position were calculated. Considering the neutral position as the baseline value, the percentage of deviation from the baseline value was calculated for each tilted/rotated position. Linear regression analysis was used to evaluate the relationship between the degree of tilted/rotated angles of the vertebrae and BMD values. For all tests, differences with p values less than 0.05 were considered significant.

Results

BMD values with respect to different degrees of lordotic and kyphotic curvatures, as well as lateral and axial rotations for the L1–L4 segments are shown in Figs. 1–4, respectively.

Discussion

Previous studies have tried to investigate the effects of projectional presentation of the spine on BMD measurements mainly by examining the custom-built phantoms or patients with scoliosis. However, these studies suffered from several limitations, such as confounding factors in human studies. These include the effects of patient body habitus, age, sex, menopausal status, other underlying diseases and medical or surgical treatments, facet osteoarthritis, and endplate sclerosis, which may have a significant impact on BMD assessment with DXA scanning. Determining the actual effects of these confounding factors on the final results of DXA scanning is impractical in clinical settings. Studies on patients with scoliosis have been limited by the fact that, along with coronal deformity, many of these patients have significant vertebral body rotation as well, which could theoretically increase the apparent vertebral body

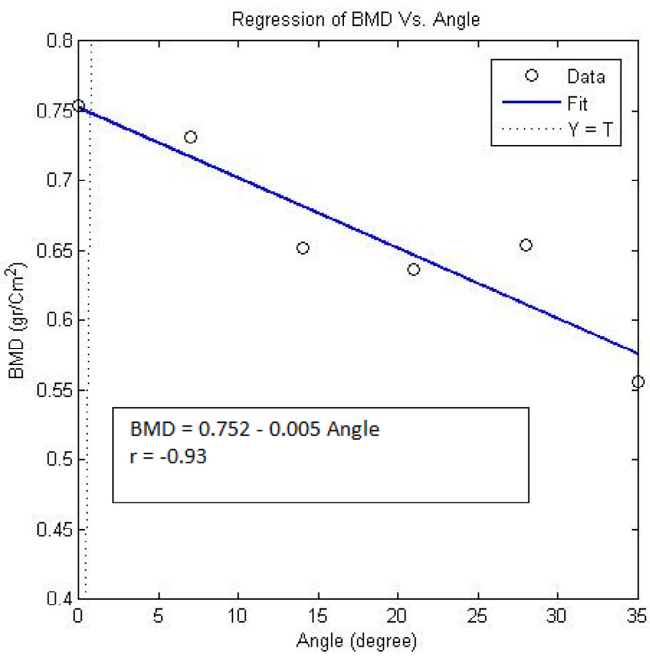

Fig. 1. Bone mineral density values of L1–L4 segments with respect to different degrees of lordotic curvature.

area and falsely decrease the estimated BMD of the target area *(8)*. Phantoms are designed to represent human spine anatomy in shape, proportion, and structure as well as density, which enables thorough analysis of imaging systems. However, currently available custom-built phantoms are also unavailable to mimic all these clinicopathological variations. In fact, custom-built phantoms are also not the perfect representative of the human body with its complex structure, and materials that comprise most anthropomorphic phantoms are not completely compatible with the osseous structure of the human spine, limiting interchangeable comparison of the results of custom-built phantoms with the human body. Given these limitations, in our study we aimed to investigate the effects of lumbar vertebral positioning on BMD measurements by DXA in a human cadaveric spine phantom to reduce the abovementioned confounding factors.

We found that projectional DXA measurements of BMD are significantly affected by the positioning of lumbar spine. Lordotic curvature has the most severe effects on the BMD values (Fig. 1), but it is also true for axial and lateral rotational scolioses as well as kyphotic curvature in lesser degrees. More specifically, we found that

- Increasing the lordosis causes a false reduction in BMD results (Fig. 1), likely due to decreasing BMC. In the lordosis and kyphosis malpositionings, the scanned areas of the vertebrae are approximately constant. In these malpositionings, the distances of the vertebrae from the X-ray tube window and the detector were changed. The measured BMC values could be changed by the vertebrae displacements. BMC per scanned area is considered as BMD (BMD = BMC/area). So, BMD results are directly proportional to measured BMC values. In these circumstances, the reduction in BMD values can be as high as 17.5%.
- Increasing the severity of kyphosis leads to a false decrease in BMD values (Fig. 2), again likely due to decreasing BMC. This false reduction of BMD value can be as high as 11.5%.
- Increasing the degree of lateral rotational scoliosis results in a false decrease in BMD results (Fig. 3) up to 10.8%. Increasing the degree of axial rotational scoliosis results in a false increase in BMD results (Fig. 4) up to 9.6%.

In the present study, the changes of the BMD values were evaluated for different lumbar vertebral malpositionings. Based on these results, clinicians and radiologists could determine the magnitudes of the false estimation (overestimation or underestimation) in the BMD measurements for the patients with spine disorders. In bone densitometry, an additional perpendicular X-ray scanning could be an appropriate approach to diagnosing the spine disorders.

These results indicate that clinicians and radiologists must take anatomical information into consideration when interpreting DXA measurements. This would help them avoiding unnecessary treatments and therapeutic expenses.

The body is considered as a 2-compartment system that includes bone and soft tissue. For each scanning area, the BMD value was determined by the Eq. (1):

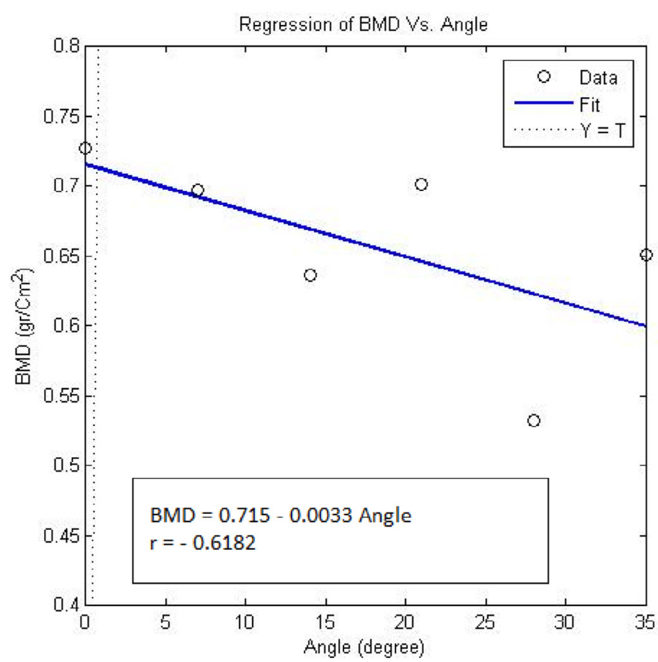

Fig. 2. Bone mineral density values of L1–L4 segments with respect to different degrees of kyphotic curvature.

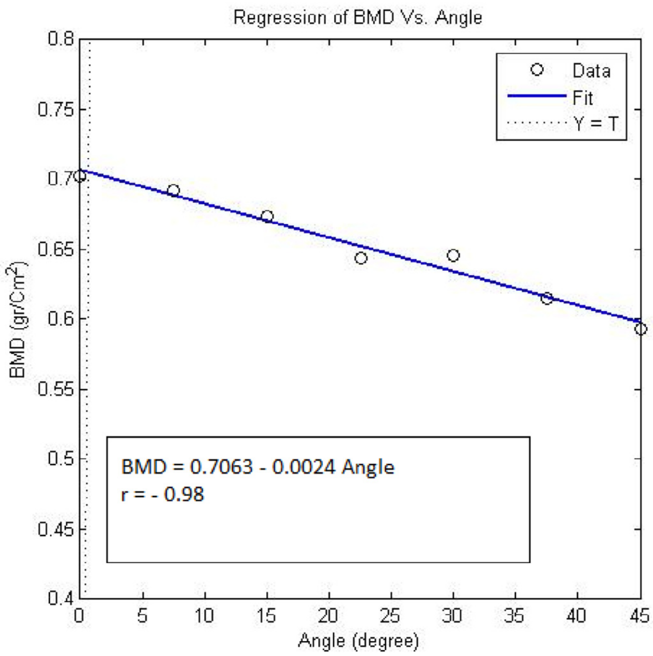

Fig. 3. Bone mineral density values of L1–L4 segments with respect to different degrees of lateral rotation.

$$I = I_0 \exp - \sum \mu_{mi} \rho_i x_i \quad (1)$$

where I is the measured intensity after passing through the sample, I_0 is the primary intensity (in the absence of the materials), x_i, μ_{mi}, and ρ_i are the thickness, mass attenuation coefficient, and density of each compartment, respectively. Bone densitometry is performed by a dual-energy X-ray unit, and this equation must be solved for both of the energy values.

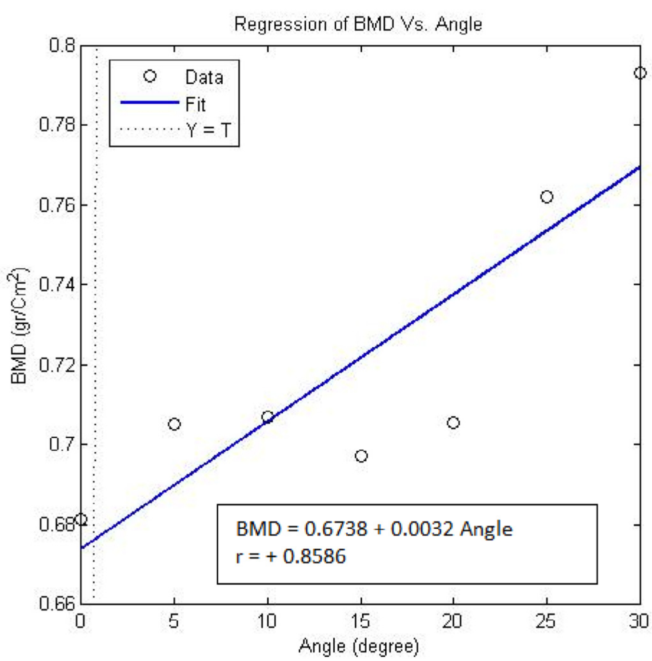

Fig. 4. Bone mineral density values of L1–L4 segments with respect to different degrees of axial rotation.

In this equation, the effects of the constant background factors (such as the changes of the primary X-rays beams over the scanning area for a fan-beam scanning) were eliminated. The pencil beam scanning is the most accurate method, but it is so time-consuming. Fan-beam scanning method is the conventional approach used in the bone densitometry. In the fan-beam scanning method, all of the scanning directions are not perpendicular to the scanning planes and an unfavorable penumbra appeared on the edge of the vertebrae. The penumbra regions changed in the different scoliosis disorders and could cause changes in the BMD measurements. A 1-dimensional array of the detectors is used to make a fair compromise between the penumbra artifact and scanning speed. The results of the scanning units with a 1- or 2-dimensional array of detectors could be affected by these factors. A part of the discrepancy between the results of previous human and phantom studies could be the results of the scanning setups.

The advantage of our study over prior publications is the fact that we used less increment intervals (5° as opposed to 7.5° in the study of Cheng et al *(3)*). To our knowledge, our study is the only one investigating the effects of complex rotational deformities of the lumbar spine (consisting of lordosis and kyphosis, and lateral and axial scoliosis) on the BMD measurements on the same subject. Another limitation of the Girardi et al study was the fact that they did not remove the soft tissues, and the thickness and composition of the cadaveric soft tissues were not evaluated *(4)*. Another limitation of human studies is the fact that adjacent vertebrae are connected to each other via facet joints; therefore, the calculation of L2–L4 BMD in vivo includes the overlapping distal part of L1 and the proximal part of L5.

There are few limitations in the present study. First, our phantom embedded in the water bath may not exactly model the human lumbar spine, mainly because of the difference between water's uniform attenuation and nonuniform attenuation of human soft tissues. Second, in our study only frontal projectional (anterior–posterior) scanning was performed, whereas in some diagnostic imaging centers lateral scanning is also carried out for the lumbar spine BMD measurement.

In conclusion, we found that projectional DXA measurements of BMD are significantly affected by the positioning of the lumbar spine, more severely affected not only by kyphotic curvature but also by axial and lateral rotational scolioses as well as lordotic curvature. To achieve the most accurate scanning results, the error sources and abnormal positioning should be identified and minimized as much as possible. If not correctable, they should be taken into consideration while interpreting the results.

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