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Original Article

Vertebral Body Compressive Strength Evaluated by Dual-Energy X-Ray Absorptiometry and Hounsfield Units In Vitro

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Abstract

Dual-energy X-ray absorptiometry (DXA) and Hounsfield unit (HU) are 2 technologies used in vivo to assess bone mineral density and to predict fracture risk. However, few in vitro studies focus on the difference between the 2 technologies in the ability to determine vertebral body compressive strength. Forty-two lumbar vertebrates were harvested from 7 mature goats. All the vertebrae were imaged using clinical computed tomography and assessed by DXA subsequently. The individual vertebral body was then mechanically tested to failure in compression, to determine ultimate load and stress. HU has a moderate correlation with DXA ($r = 0.64$). DXA has significant associations with ultimate load and stress ($r = 0.59$ and 0.69, respectively). Significant positive linear correlations were also found between HU and ultimate load ($r = 0.65$) and stress ($r = 0.81$). There was no significant difference between HU and DXA to predict the ultimate load ($t = 0.56, p = 0.577$) or the ultimate stress ($t = 1.62, p = 0.112$). HU has an equal predictive value as the DXA for whole vertebral body compressive strength. This work supports the application of the HU measurement using clinical computed tomography imaging technology to assess bone strength and fracture risk.

Key Words: Compressive strength; dual-energy X-ray absorptiometry; Hounsfield units.

Introduction

Bone mineral density (BMD) of the spine is usually used to predict fracture risk. In clinical practice, the BMD is usually estimated by dual-energy X-ray absorptiometry (DXA) and Hounsfield unit (HU). DXA is the long-time standard method since 1987 *(1)*, whereas HU measurement was proposed in 2011 *(2)*. The predictive ability of DXA for osteoporotic vertebral fractures has been assessed and proven in a large number of epidemiological studies. A well-known meta-analysis of a prospective fracture study by Marshall et al provided informative evidence *(3)*. Marshall et al concluded that spine BMD by DXA could predict vertebral spine fractures (relative risk = 2.3, 95% confidence interval: 1.9–2.8). HU measurement is another method proposed by Schreiber et al to assess spine BMD *(2)*. Based on the clinical computed tomography (CT) images, the average HU value of 3 different levels of 1 vertebra is regarded as the whole vertebra's BMD. As an additional information of clinical CT without any additional cost or radiation exposure, the ability of HU has been explored in several studies, especially in assessing fracture risk *(4)*. Meredith et al found that lower HU values on regional and global vertebral bodies were associated with the adjacent-segment fractures after spinal fusion *(4)*. Besides, Liu et al followed up 132 patients treated with vertebroplasty for osteoporotic fractures *(5)*. Liu et al found a significant correlation between HU measurement and subsequent compression fracture after the vertebroplasty. Both HU and DXA are used in vivo to assess the fracture risk, but the difference in the predictive ability between the 2 technologies is still unknown.

To date, many biomechanical tests support the epidemiological studies of the association between DXA and fracture risk. BMD based on DXA has been shown to be

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correlated to the mechanical properties of vertebrae, determined by compression tests in vitro, with reported correlation coefficients ranging from 0.47 to 0.92 *(6,7)*. As for HU measurement, there is only 1 study that has focused on the correlation of HU measurement with compressive strength since it was proposed. Schreiber et al found a linear correlation between HU value and compressive strength *(2)*. However, in Schreiber et al's study, polyurethane foam was used to imitate the human bone. Polyurethane foam may be unable to provide enough mechanical data of the vertebral body.

Bone density may account for the ability to predict fracture risk due to its relatively high correlation with compressive strength of vertebral bone *(8,9)*. When determining the HU value at different levels of the vertebrae, the region of interest (ROI) was placed on the cancellous bone region on the transverse section while excluding the cortical margin, osteophytes *(2)*. Thus, HU measurement is a method to determine cancellous density. However, DXA, as a planar measurement, includes cancellous and cortical bones, even the osteophytes. Although there is a moderate correlation between them, HU measurement focuses on the cancellous density, whereas DXA measures the density of the whole body including the posterior elements. Whether the difference between HU and DXA affects the predictive ability for compressive strength is still not clear.

Approximately, 15% of males and 51% of females among the patients undergoing spine surgery have osteoporotic fractures *(10)*. The fracture after spinal fusion or vertebroplasty and cage subsidence, which is also related to bone strength, are unavoidable issues for spine surgeons. Thus, adequate assessment of BMD and fracture risk should be incorporated in preoperative planning. To achieve this objective, HU measurement and DXA are 2 options that are already being applied in clinical practice. HU measurement based on the routine CT before spinal surgery may has great potential. But, before promoting the use of HU measurement in clinical practice, we need to clarify whether the ability to assess compressive strength is obviously different or not between DXA and HU measurement.

The primary objective of the present study is to study the possible relationship between HU and the compressive strength of vertebrae. The secondary objective of the present study is to study whether a difference exists between HU and DXA in the evaluation of vertebrae's compressive strength.

Methods

Clinical CT Imaging and HU Measurement

The present study was approved by the Committee of Medical Ethics and the institutional review boards of our hospital. Seven frozen goat lumbar spines were obtained from a local abattoir. Spines were kept frozen during storage. All spines were scanned at a GE LightSpeed QX/i MSCT (General Electric, Milwaukee, WI) with a tube voltage of 120 kV and a tube current of 250 mA. This is typically the same equipment and parameters by which the patients' spines would be imaged. For each vertebral body, the images were reconstructed to achieve the transverse section of the vertebral body.

HU values were measured according to the methodology described by Schreiber et al *(11)*. An elliptic ROI was placed on the transverse section of vertebral body, including the largest possible cancellous bone region, while excluding the cortical margin, osteophytes. The HU value of the ROI was calculated automatically by the picture archiving and communication system (Centricity ®RIS CE, GE Healthcare, Milwaukee, WI). Three separate sections of each vertebra were measured. The mean HU value of the 3 ROIs was regarded as the vertebral body HU (Fig. 1).

ROIs were placed on 3 locations: immediately inferior to the superior end plate (Fig. 1A), in the middle of the vertebral body (Fig. 1B), and superior to the inferior end plate (Fig. 1C). The HU value of each ROI was calculated automatically by Picture Archiving and Communication Systems. The mean HU value was regarded as the BMD according to the protocol described by Schreiber et al *(2)*.

DXA

The DXA measurements were performed on a Hologic Discovery A scanner (Hologic, Bedford, MA). Before DXA scanning, the spines were thawed at ambient temperature (22°C) for 24 h. Then, the spines were placed in an equilibrium liquid-filled container to make sure that the vertebrae were in a supine anatomical position relative to the radiation source. The BMD (gram per square centimeter) of each individual vertebra was calculated by the scanner software.

Compression Testing

Before dissection, 7 spines were thawed at ambient temperature (22°C) overnight. All soft tissues were removed from the spines and each individual vertebra was carefully dissected. A total of 42 vertebral columns were excised from the goat from the lumbar section. Posterior elements were dissected at the base of the pedicles with a high-speed saw.

After the disc was removed, cross-sectional area (CSA) of the end plate were determined by the method proposed by Callaghan and McGill *(12)*. The CSA was calculated using the equation for surface area of an ellipse:

$$\frac{\pi ab}{4}$$

where a is the anterior posterior length and b is the medial–lateral width of the vertebral end plate.

Each vertebral body compressive strength was determined with an MTS servo controlled hydraulic material testing machine (Model 8874; Instron Corporation, Norwood, MA). Vertebrates were placed between a rigid upper platen and a self-aligning lower platen. Before the compressive test, a small compressive preload (<40 N) was