

Original Article

Evaluation of Bone Mineral Density and Bone Structure in the Cervical and Thoracic Spine

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Dropped head syndrome, which has been increasingly reported in recent years, requires correction of cervical kyphosis and may require long-range fixation extending from the cervical to the thoracic spine. Assessing vertebral bone structure may be important for preventing instrumentation failure in the upper thoracic spine, which is a potential complication of surgery. In this study, we evaluated volumetric bone mineral density, trabecular bone porosity, and cortical calcification in the cervical and upper thoracic spine using three-dimensional (3D) trabecular structure measurement software. The study included 79 patients with cervical spine disorders who underwent various surgical procedures and preoperative imaging, including dual-energy X-ray absorptiometry and computed tomography (CT) scans from C3 to Th3. Quantitative analysis using specialized software assessed volumetric bone mineral density and trabecular and cortical bone parameters, and statistical analyses were performed to examine correlations between imaging metrics and indicators of bone fragility. Two-dimensional CT evaluation revealed different trends between cancellous and cortical bone in the cervical and thoracic spine, suggesting that detailed 3D evaluation may also be important.

Key words: cervical spine, volumetric bone mineral density, three-dimensional trabecular structure measurement

In cases of cervical spondylotic myelopathy (CSM) with instability or kyphosis, decompression combined with cervical fixation has been reported to yield better postoperative outcomes than decompression alone (*i.e.*, laminoplasty) [1]. Suda *et al.* reported poorer clinical outcomes after laminoplasty alone in patients with CSM and local kyphosis of ≥ 13 degrees [2]. In addition, patients with CSM classified as K-line (–) on sagittal MRI have been reported to have poorer outcomes than K-line (+) cases [3]. These findings suggest that, in selected cases of cervical deformity, fixation in addition to decompression may be necessary.

Dropped head syndrome, which has been increasingly reported in recent years, is one such condition

and requires correction of cervical kyphosis. In some cases, adequate correction requires long-range fixation extending from the cervical spine to the upper thoracic spine [1,4,5]. In particular, the T1-slope in cervical kyphosis is considered an important parameter for correction of the C2-C7 angle and for determining the optimal cervical lordosis angle [6]. When such long-range fixations are used, the upper thoracic vertebrae may serve as the distal instrumented vertebra (DIV). In such cases, instrumentation failure occurred in the upper thoracic vertebrae (Fig. 1). However, few studies have evaluated bone fragility from the cervical spine to the upper thoracic spine. Therefore, evaluation of the vertebral body structure of the upper thoracic vertebrae, which may serve as the DIV, is important for the suc-

Received November 22, 2025; accepted March 23, 2026.

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Conflict of Interest Disclosures: No potential conflict of interest relevant to this article was reported.



Fig. 1 A case of instrumentation failure after long-range fixation for dropped head syndrome (White arrow: vertebral fracture and collapse).

cess of corrective fixation surgery. Assessing bone fragility in the upper thoracic spine is challenging, and current assessment often relies on dual-energy X-ray absorptiometry (DXA) of the lumbar spine and femur. Alternatively, Hounsfield units (HU) on cervical and thoracic computed tomography (CT) scans may be used. Takasu *et al.* reported the usefulness of CT-based assessment of trabecular bone structure, including trabecular thickness and number, for evaluating vertebral bone fragility in patients with multiple myeloma [7]. In the present study, we used a revised version of the software of Takasu *et al.* to evaluate volumetric bone mineral density (BMD), trabecular bone porosity, and cortical bone calcification in the cervical and upper thoracic spine, thereby enabling a more detailed assessment of bone fragility.

Methods and Methods

Study participants. The study included consecutive 79 patients (36 females and 43 males) with cervical

spine disease who underwent various surgical procedures between 2021 and 2024 (Table 1). The inclusion criteria were patients who had dropped head syndrome, cervical spondylotic myelopathy, cervical spondylotic radiculopathy, or atlantoaxial subluxation. Patients with ossification of the posterior longitudinal ligament (OPLL), infection, or reoperation were excluded from the study. This study was approved by the Institutional Review Board of the author's affiliated institution (No. R04-256), and informed consent was obtained from all patients.

Surgical procedure. In cases of cervical spondylotic myelopathy, laminoplasty (the modified Kurokawa's method) was performed in 45 cases and laminoplasty + posterior fixation in 17 cases. Anterior-posterior fusion surgery was performed in 14 patients with dropped head syndrome. In 3 cases of cervical spondylotic radiculopathy, anterior cervical discectomy and fusion (ACDF) was performed.

Radiological measurement. DXA of the lumbar spine and femoral neck was performed for all patients. CT was performed preoperatively from C3 to Th3 using a B-MAS CT bone mineral reference phantom (B-MAS200; Kyotokagaku Co., Kyoto, Japan) containing calibration objects with equivalent densities of 0, 50, 100, 150, and 200 mg/cm³ calcium hydroxyapatite. CT images were obtained using the following settings: tube voltage, 120 kV; pitch factor, 0.637; and collection slice thickness, 0.5 mm. The thin-slice data were reconstructed using the following parameters: high-frequency enhancement function, FC30; reconstruction slice thickness, 1 mm; and reconstruction interval, 1 mm. BMD and trabecular structure were measured for each vertebral body from C3 to Th3 (C3-Th1: n=79 vertebral bodies; Th2: n=72 vertebral bodies; Th3: n=60 vertebral bodies) using three-dimensional (3D) trabecular structure measurement software (TRI/3D-BON-

Table 1 Patient demographics

Patient demographics			P-value
Patients (n = 79)	M : 43	F : 36	
Age (years)	72.9 ± 10.4	76.1 ± 10.4	0.1302
L-T score (SD)	0.84 ± 1.67	-0.85 ± 2.30	0.0008
F-T score (SD)	-1.29 ± 1.06	-2.34 ± 1.18	0.0003

Data are presented as mean ± SD. The Mann-Whitney *U* test was used for comparisons.

F, female; M, male; SD, standard deviation; L-T score, lumbar T score; F-T score, femoral neck T score.

FCS; Ratoc System Engineering Co.) (Fig. 2). The region of interest (ROI) for each vertebral body was set by selecting the entire vertebral body in the horizontal section and 2/3 of its height in the sagittal and coronal sections (Fig. 3). Evaluation indicators included volumetric BMD (vBMD: mg/cm^3), trabecular bone assessment using the V^*_{m} space (mm^3) and V^*_{tr} (mm^3), and cortical bone assessment using cortical bone tissue mineral density (CB-TMD: mg/cm^3). The V^*_{m} space is the average volume of the marrow cavity that can be seen from any point within the intertrabecular space in the bone marrow in all directions without being obstructed by the trabecular bone using the star volume

method devised by Gundersen *et al.* [8]. V^*_{tr} represents the average volume of continuous trabecular bone that is not torn in any direction from a point in the trabecular bone [8,9]. Specifically, indicators of osteoporosis in trabecular bone include the widening of trabecular spaces and decreased trabecular bone volume. The HU value was measured as the average of three locations on the sagittal plane of the vertebral body: immediately below the endplate, at the center of the vertebral body, and immediately above the endplate, as reported by Schrieber *et al.* [10].

Statistical analysis. All statistical analyses were performed using StatFlex Ver. 6 (Artech Co., Osaka,

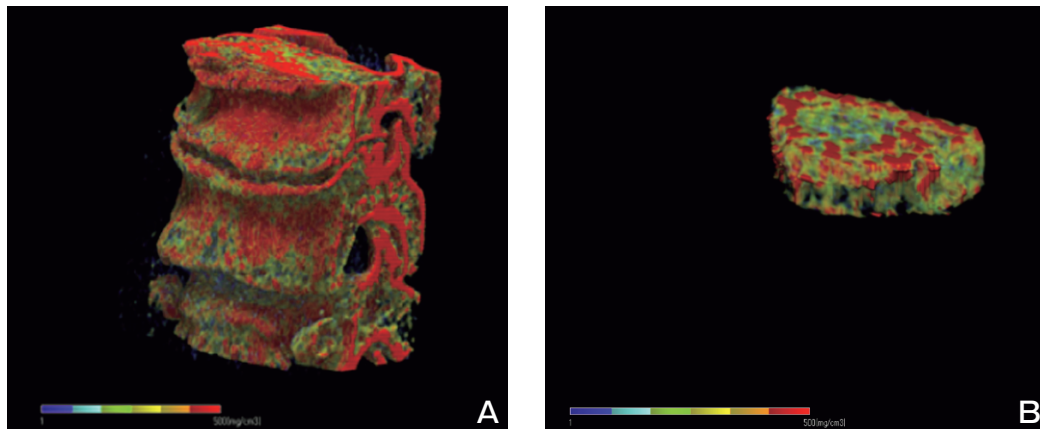


Fig. 2 Three-dimensional models of bone mineral density using TRI/3D-BON-FCS (Ratoc System Engineering). (A) Whole spine; (B) C4. Red areas indicate the highest BMD, while the blue areas indicate the lowest BMD.

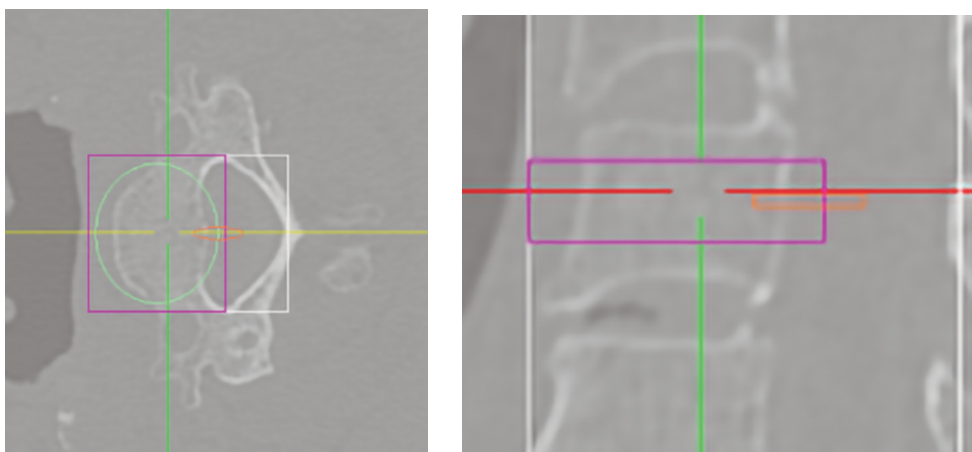


Fig. 3 Measurement range for the cervical spine in 3D trabecular bone structure measurement software. The region of interest (ROI) was defined as the vertebral body area (green area) enclosed within the purple box (The ROIs in the sagittal and coronal sections were set at 2/3 of the vertebral body height).

Japan). Correlations between DXA-derived T-scores (lumbar spine and femoral neck) and vBMD (mg/cm^3), V^*_{m} space (mm^3), V^*_{tr} (mm^3), and CB-TMD (mg/cm^3) were assessed using Spearman's correlation coefficient. Furthermore, we examined the correlation between V^*_{m} space (mm^3), V^*_{tr} (mm^3), and HU values. We also evaluated the vBMD (mg/cm^3), V^*_{m} space (mm^3), V^*_{tr} (mm^3), and CB-TMD (mg/cm^3) of each vertebral body and differences from the cervical spine to the upper thoracic spine using the Mann-Whitney U test. Statistical significance was set at $p < 0.05$.

Results

The study included 79 patients: 43 men (mean age 72.9 years) and 36 women (mean age 76.1 years). The T-score of the lumbar spine was 0.84 ± 1.67 SD for men

and -0.85 ± 2.30 SD for women, while the T-score of the femoral neck was -1.29 ± 1.06 SD for men and -2.34 ± 1.18 SD for women (Table 1). For vertebral bodies C3 to Th3, correlations between the measured parameters and lumbar spine T-scores were weak (Fig. 4A). Femoral neck T-scores were also only weakly correlated with the measured parameters of the C3-Th3 vertebral bodies (Fig. 4B). The correlation between the HU values of the cervical spine (C3-7) and vBMD was strongly positive (Spearman's correlation coefficient [r_s] = 0.904). The correlation between the HU values of the thoracic spine (Th1-3) and vBMD was also strongly positive (r_s = 0.895). The correlation between the HU values of the cervical spine (C3-7) and V^*_{tr} (an indicator of osteoporosis) was positive (r_s = 0.843). At the same time, the V^*_{m} space showed a negative correlation (r_s = -0.847). Furthermore, the correlation between the cervical spine (C3-7) HU

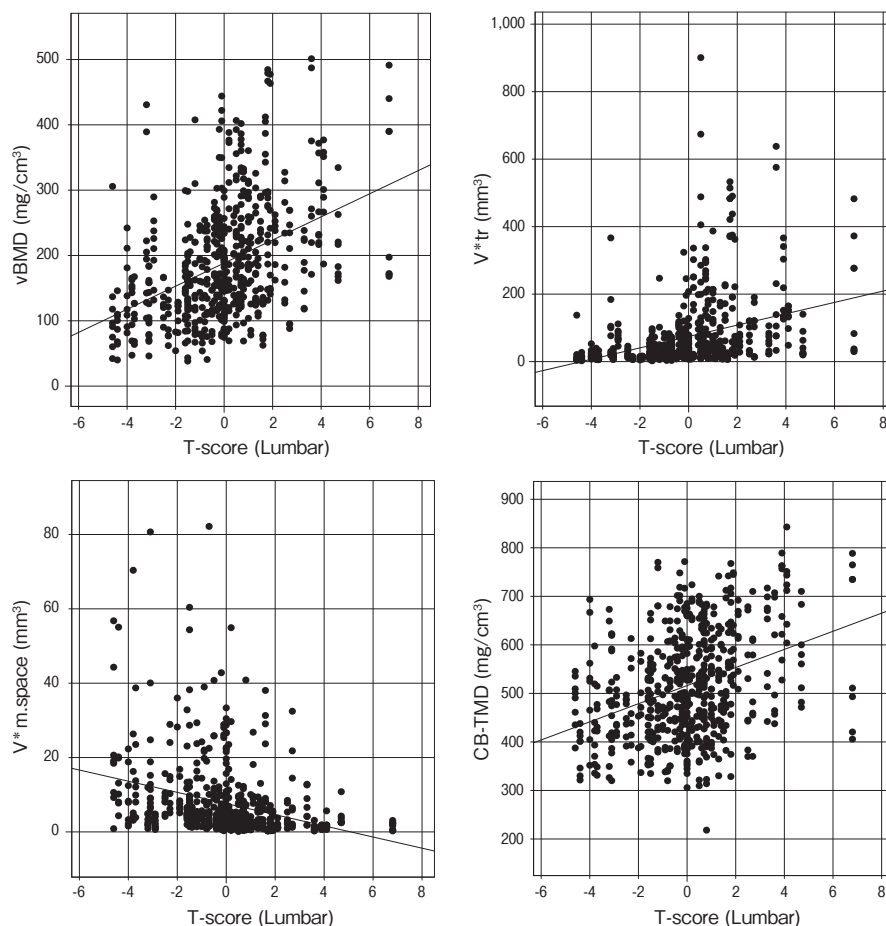


Fig. 4A Correlation between measurements and lumbar spine T-score using Spearman's correlation coefficient. r_s values for each measure were as follows: vBMD: 0.420; V^*_{tr} : 0.434; V^*_{m} space: -0.400 ; CB-TMD: 0.326.

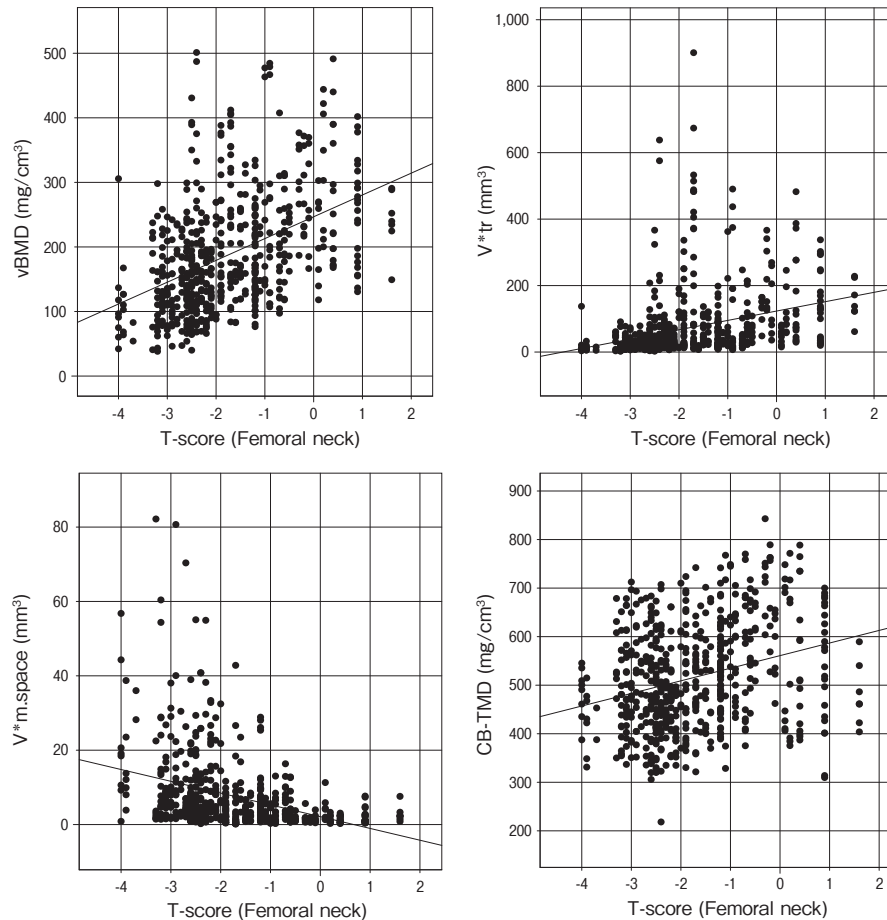


Fig. 4B Correlation between measurements and femoral neck T score using Spearman's correlation coefficient. r_s values for each measure were as follows: vBMD: 0.471; V^*tr : 0.492; $V^*m.space$: -0.454; CB-TMD: 0.269.

values and CB-TMD was positive ($r_s=0.500$) (Fig. 5A). The correlation between HU and V^*tr (an indicator of osteoporosis) in the thoracic spine (Th1-Th3) was positive ($r_s=0.835$), while that between HU and the $V^*m.space$ was negative ($r_s=-0.894$). In contrast, a weak positive correlation was observed between CB-TMD and HU ($r_s=0.273$) (Fig. 5B).

In men, among the cervical and upper thoracic vertebrae, vBMD and V^*tr were highest at C4 (262.80 ± 1.47 mg/cm³ and 153.70 ± 146.01 mm³, respectively), whereas $V^*m.space$ was lowest at C4 (2.70 ± 2.42 mm³). CB-TMD was highest at C5 (635.60 ± 93.10 mg/cm³) (Table 2). In women, vBMD was also highest at C4 (vBMD: 218.54 ± 81.83 mg/cm³), and $V^*m.space$ was lowest at C4 (3.28 ± 2.58 mm³). CB-TMD was highest at C5 (635.60 ± 93.10 mg/cm³) (Table 3). Both men and women showed superior osteological structures in

many items at C4, whereas the lower cervical vertebrae (C6, C7) exhibited lower values. Furthermore, the values gradually decreased from the cervical to the thoracic spine, with Th3 exhibiting the lowest value. Compared to C4, the vertebral bodies from C7 downward showed significantly lower values (Tables 2 and 3). A tendency toward decreased BMD and trabecular bone structure was observed from the lower cervical to the thoracic spine.

Discussion

Takasu *et al.* evaluated both the vertebral bone structure and fragility after multiple myeloma treatment using the same software [7]. In this study, we used a revised version of their software to investigate trabecular bone thickness, number, and stiffness, and con-

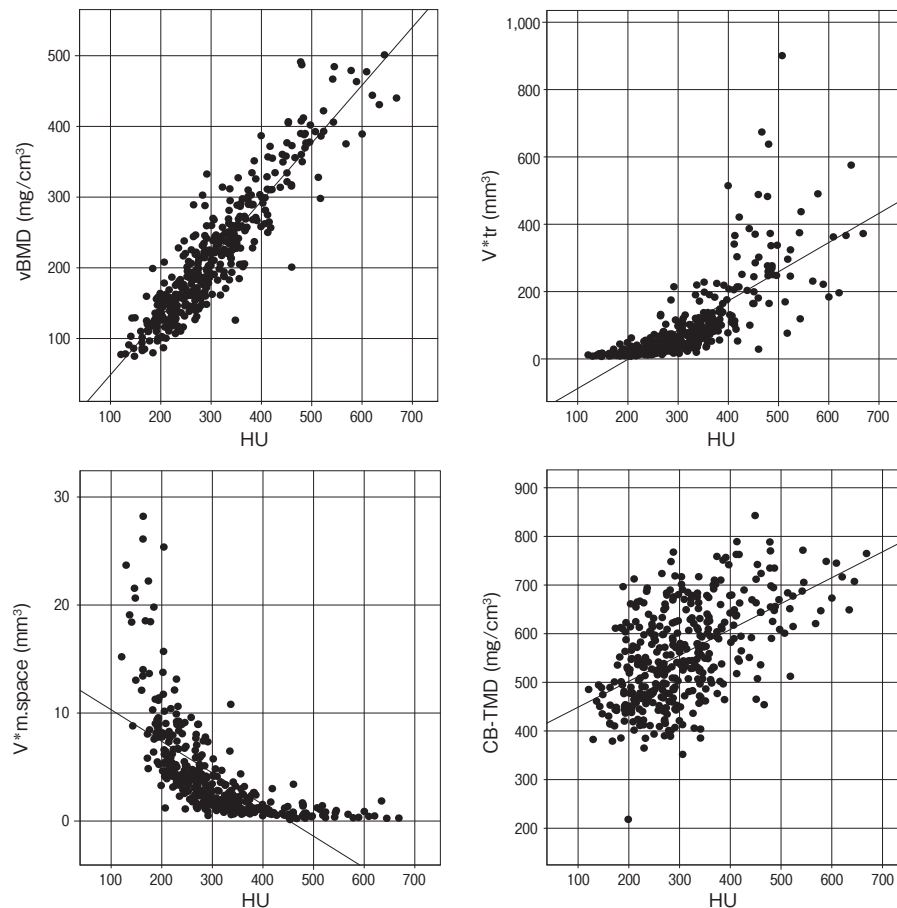


Fig. 5A Correlation between C3-7 measurements (vBMD, V^*tr , $V^*m.space$, CB-TMD) and HU using Spearman's correlation coefficient. r_s values for each measure were as follows: vBMD: 0.904; V^*tr : 0.843; $V^*m.space$: -0.847; CB-TMD: 0.500.

cluded that the evaluation of bone fragility is effective for assessing fracture risk. Past reports measuring cervical vertebral BMD have shown that the BMDs of C4 and C5 were higher than those of other cervical vertebrae [11-14]. These previous reports indicated that cervical vertebral body BMD was highest at C5 and decreased in the direction of C3 and C7 [11-13]. Similarly, William *et al.* found that the C4 and C5 vertebral bodies had high values, C3 and C6 had lower values, and C7 had the lowest values [14]. A study on younger subjects also indicated that BMD at C6 was lower than BMD at C3-C5 in young females, while in young males, BMD values were greater at C4 and C5 than at C3 and C6, and BMD was significantly greater at C3 than C6 [15]. Significantly lower BMD of C7 in comparison to C4-C6 using DXA has also been reported in cadaver specimens (mean age 71 years; 9 males and

6 females) [16]. A possible reason for this difference in BMD is that C3-C7 were exposed to different in vivo loads, with C4 and C5 having the highest loads. Although these previous reports only used vBMD to assess bone status, in the present study we performed separate analyses of trabecular and cortical bone and examined bone structural parameters. In our study, the C4 group demonstrated superior BMD and trabecular bone microstructure. All vertebral bodies with superior BMD exhibited lower $V^*m.space$ (intertrabecular cavity) and higher V^*tr (trabecular bone volume) in this study. The upper thoracic spine (Th1-Th3) exhibited lower values than C7. Previous studies on vertebral bone have primarily focused on young populations, and no research has specifically examined the structure of the cervical and upper thoracic spine in elderly individuals [13-15]. Furthermore, the relationship between trabec-

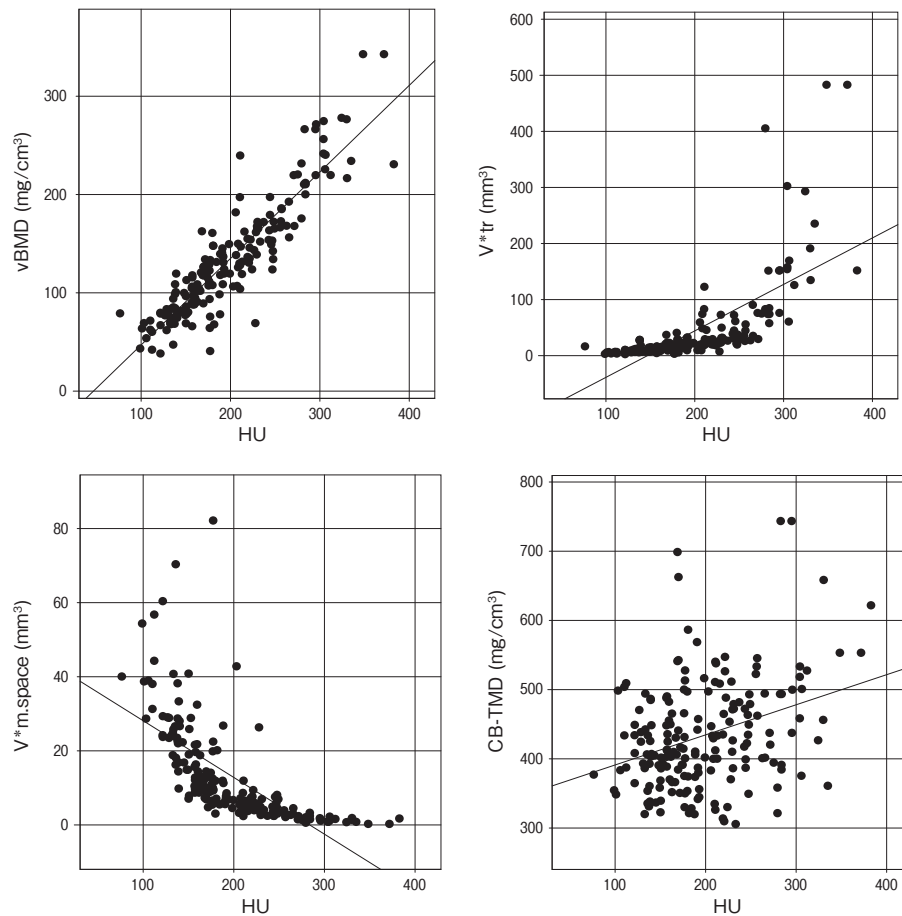


Fig. 5B Correlation between Th1-3 measurements (vBMD, V^*tr , $V^*m.space$, CB-TMD) and HU using Spearman's correlation coefficient. r_s values for each measure were as follows: vBMD: 0.895; V^*tr : 0.835; $V^*m.space$: -0.894; CB-TMD: 0.273.

ular bone structures assessed by 3D CT and simplified HU values has not been thoroughly investigated. Because cervical spine fractures are less frequent than those in the thoracic or lumbar spine, there are few reports assessing bone fragility in the cervical region. Therefore, detailed examination of the cervical spine itself is rare. In this study, C7 showed lower values than the other cervical vertebrae (C3-C6), suggesting that similar decreases may occur in the upper thoracic spine as well. As a result, Th1-3 showed even lower values than C7. This study targeted patients with cervical kyphosis or cervical spondylosis (average age: 70 years). In cases of dropped head syndrome with a markedly increased T1 slope, it is essential to extend the DIV to a lower thoracic level, beyond T1, to ensure adequate correction and stability. Bone parameters of the vertebral bodies in the cervical or thoracic spine can be esti-

mated from BMD in the lumbar spine or femur or by using CT values (HU). The correlation coefficients between bone parameters of the cervical and thoracic spine and T-scores of the lumbar spine and femoral neck did not exceed 0.4 in our analysis. In contrast, HU showed high correlations with V^*tr and $V^*m.space$ (greater than 0.5) in our study. HU values have gained attention as a simple and versatile parameter for evaluating BMD in the thoracolumbar spine [17]. This study used the average of three slices at the level of the vertebral body center and vertebral end plate in the cervical and thoracic spine. The software used in this study enables 3D volumetric examination of the vertebral bodies and allows for a more comprehensive assessment of their condition. Although the lumbar spine DXA data is affected by cortical calcification (bone spurs), this software can separate trabecular bone regions from

Table 2 Indexes of bone trabecular structure and BMD in each spine of males

Males	vBMD (mg/cm ³)	V*m space (mm ³)	V*tr (mm ³)	CB-TMD (mg/cm ³)
C3	246.96 ± 87.75 <i>p</i> = 0.4344	3.25 ± 2.96 <i>p</i> = 0.3713	112.53 ± 98.65 <i>p</i> = 0.2217	571.30 ± 95.81 <i>p</i> = 0.2940
C4	262.80 ± 91.47 —	2.70 ± 2.42 —	153.70 ± 146.01 —	593.86 ± 105.72 —
C5	254.52 ± 90.14 <i>p</i> = 0.7007	2.76 ± 3.05 <i>p</i> = 0.9209	121.28 ± 124.28 <i>p</i> = 0.2861	635.60 ± 93.10 <i>p</i> = 0.1072
C6	226.79 ± 79.30 <i>p</i> = 0.0652	4.06 ± 5.29 <i>p</i> = 0.2861	96.04 ± 91.79 <i>p</i> = 0.0556	588.91 ± 87.853 <i>p</i> = 0.7007
C7	191.83 ± 72.56 <i>p</i> = 0.0003	5.51 ± 6.18 <i>p</i> = 0.0095	90.15 ± 151.64 <i>p</i> = 0.0017	504.38 ± 92.12 <i>p</i> = 0.0001
Th1	159.95 ± 60.88 * <i>p</i> < 0.0001	7.27 ± 7.36 * <i>p</i> < 0.0001	61.08 ± 90.39 * <i>p</i> < 0.0001	433.42 ± 76.70 * <i>p</i> < 0.0001
Th2	147.25 ± 63.64 *	11.28 ± 11.07 *	64.18 ± 105.92 *	438.14 ± 93.81 *
Th3	136.53 ± 53.359 *	13.51 ± 12.33 *	49.89 ± 94.77 *	488.41 ± 96.08 *

This table showed statistical evaluations between C4 and each other vertebral level in male using the Mann-Whitney *U* test (*p* < 0.05 was considered statistically significant). vBMD, V*tr of C4 is higher and V*m space of C4 is lower than all other vertebrae. Since C4 had better values than the other vertebrae, the values were evaluated between C4 and each other's vertebral level.

C7, Th1, Th2 and Th3 showed significant differences in items compared to C4. (*: *p* < 0.0001)

Table 3 Indexes of bone trabecular structure and BMD in each spine of females

Females	vBMD (mg/cm ³)	V*m space (mm ³)	V*tr (mm ³)	CB-TMD (mg/cm ³)
C3	188.39 ± 67.42 <i>p</i> = 0.0906	5.03 ± 4.98 <i>p</i> = 0.0999	53.56 ± 49.95 <i>p</i> = 0.3122	501.44 ± 73.81 <i>p</i> = 0.0054
C4	218.54 ± 81.83 —	3.28 ± 2.58 —	68.29 ± 61.67 —	554.78 ± 78.51 —
C5	213.50 ± 95.53 <i>p</i> = 0.4397	4.24 ± 3.76 <i>p</i> = 0.4543	72.78 ± 109.64 <i>p</i> = 0.2915	590.51 ± 87.56 <i>p</i> = 0.0695
C6	198.51 ± 92.02 <i>p</i> = 0.1108	5.29 ± 4.29 <i>p</i> = 0.0542	75.08 ± 123.20 <i>p</i> = 0.1136	562.82 ± 81.81 <i>p</i> = 0.7129
C7	160.28 ± 67.15 <i>p</i> = 0.0007	7.02 ± 5.43 <i>p</i> = 0.0011	46.83 ± 58.13 <i>p</i> = 0.0273	466.49 ± 56.46 * <i>p</i> < 0.0001
Th1	129.10 ± 57.45 * <i>p</i> < 0.0001	12.67 ± 12.17 * <i>p</i> < 0.0001	30.51 ± 32.75 * <i>p</i> = 0.0002	414.15 ± 54.84 * <i>p</i> < 0.0001
Th2	108.97 ± 44.37 *	19.77 ± 20.22 *	22.56 ± 22.72 *	403.29 ± 50.34 *
Th3	102.98 ± 53.94 *	22.27 ± 17.98 *	16.07 ± 13.78 *	441.71 ± 56.37 *

This table showed statistical evaluations between C4 and each other vertebral level in female using the Mann-Whitney *U* test (*p* < 0.05 was considered statistically significant). Similar to Table 2, vBMD, V*tr of C4 is higher and V*m space of C4 is lower than all other vertebrae. Since C4 had better values than the other vertebrae, the values were evaluated between C4 and each other's vertebral level.

C7, Th1, Th2 and Th3 showed significant differences in items compared to C4 (*: *p* < 0.0001).

cortical regions. Cancellous bone assessment using the star volume method allows the evaluation of both trabecular volume and intertrabecular cavity. Measurements using this software revealed a positive correlation between trabecular bone volume and HU values, and a negative correlation in intertrabecular cavity (Fig. 5A, 5B). The HU values showed a stronger correlation than DXA. Three-dimensional evaluation can provide a detailed assessment of the bone structure for vertebral evaluation. The results of our study showed that men had higher values than women across all measurements (Table 2 and 3), which was consistent with the DXA findings in the lumbar spine and femur. We believe that cervical and thoracic spine BMD in elderly women decreases due to a decrease in female hormones and a decrease in mechanical load caused by a decline in muscle strength and exercise habits. Inoue *et al.* reported the therapeutic effects of pharmacological treatment for glucocorticoid-induced osteoporosis (GIO) using the same methods (vBMD, Star volume, *etc.*) applied to the lumbar spine [18]. They reported that CT-based methods were superior to DXA and biochemical markers in evaluating the preventive effects on vertebral fractures. In our study, the thoracic spine (Th1-3) showed lower values than the cervical spine for all parameters. Although there have been no previous studies evaluating the bone structure of cancellous and cortical bone in the thoracic spine, evaluation of the bone structure of the thoracic spine is clearly important.

The number of older patients undergoing cervical spinal trauma and deformity surgery is increasing. Miyamoto *et al.* reported that the DXA results from two patients who developed distal junctional kyphosis (DJK) after long cervical fusion were significantly lower than those from patients who did not develop DJK [6]. Furthermore, in patients with a T1 slope of $>40^\circ$ due to decompensation of the downward spine, long fusion (LF), whose extent of fixation involves the cervical and thoracic spines, and several types of osteotomies, such as multilevel Ponte osteotomy, have been added to correct thoracic kyphosis [6]. When using the upper thoracic vertebrae as an anchor for correction and fixation of the cervical spine with severe kyphosis, it is essential to evaluate not only the T1 slope, but also the trabecular bone structure, including bone density, to determine the distal instrumented vertebra. In this study, we conducted basic research to investigate the bone quality

of the DIV. The cervical spine showed a correlation between trabecular and cortical bone mineralization values and HU. In other words, patients with higher HU values exhibited higher values of V^*_{tr} and cortical bone calcification, whereas the values of the V^*_m space were lower. There was no difference between the cervical and thoracic spine in the correlation between HU values and trabecular bone structure (V^*_{tr} , V^*_m space). However, the correlation between HU values and cortical mineralization was lower in the thoracic spine than in the cervical spine (cervical spine: $rS=0.500$; thoracic spine: $rS=0.273$) (Fig. 5A, B). Bone strength of the thoracic spine may be influenced not only by the condition of the cancellous bone but also by cortical mineralization. Therefore, when assessing bone strength in the thoracic spine, it is essential to consider both cancellous bone and cortical mineralization. Based on the present study and the related investigation by Inoue *et al.*, the assessment of thoracic vertebral bone fragility using DXA appears to have limitations. HU-based measurements are considered to reflect the structural characteristics of the cervicothoracic spine accurately; moreover, our proposed method is expected to provide an even more precise evaluation. For these reasons, we believe that not only HU-based measurements but also 3D evaluations such as those provided by this software are important.

In conclusion, we evaluated three-dimensional BMD, trabecular bone architecture, and the degree of cortical calcification across the cervicothoracic spine from C3 to Th3. The correlation between HU and trabecular bone architecture did not differ between the cervical and thoracic spine. However, the correlation between HU and the degree of cortical calcification was lower in the thoracic spine than in the cervical spine. Although bone strength has commonly been assessed using indices such as DXA and HU, these measures alone may be insufficient for evaluating the upper thoracic spine, which may serve as the DIV.

Acknowledgments. We thank the staff of the Department of Orthopedics at our institution for their helpful assistance.

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